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Sensory Adaptation to Weightlessness and Readaptation to One-g: An Overview

M.I.T./Canadian Vestibular Experiments on Spacelab-1: Part 1

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Summary

Experiments on human spatial orientation were conducted on four crewmembers of Space Shuttle Spacelab Mission 1. This introductory paper presents the conceptual background of the project, the relationship among the experiments and their relevance to a "sensory reinterpretation hypothesis". Detailed experiment procedures and results are presented in the accompanying papers in this series. The overall findings are discussed in this article as they pertain to the following aspects of hypothesized sensory reinterpretation in weightlessness: 1) utricular otolith afferent signals are reinterpreted as indicating head translation rather than tilt, 2) sensitivity of reflex responses to footward acceleration is reduced, and 3) increased weighting is given to visual and tactile cues in orientation perception and posture control.

Three subjects developed space motion sickness symptoms, which abated after several days. Head movements, as well as visual and tactile cues to orientation influenced symptoms in a manner consistent with the sensory--motor conflict theory of space motion sickness. Six short duration tests of

motion sickness susceptibility, conducted pre-flight, failed to predict sickness intensity in weightlessness. An early otolith-spinal reflex, measured by electromyography from the gastrocnemius-soleus muscles during sudden footward acceleration, was inhibited immediately upon entering weightlessness and declined further during the flight, but was unchanged from preflight when measured shortly after return to earth. Dynamic visual-vestibular interaction was studied by measuring subjective roll self-motion created by looking into a spinning drum. Results suggest increased weighting of visual cues and reduced weighting of graviceptor signals in weightlessness. Following the 10 day flight, erect posture with eyes closed was disturbed for several days. Somewhat greater visual field dependence postflight was observed for two of the crew. Postflight tests using horizontal linear acceleration revealed an increased variance in detection of acceleration. The ability of the returned crew to use non-visual lateral acceleration cues for a manual control task appeared enhanced over their preflight ability for a few days after return.

INTRODUCTION

The nearly weightless (microgravity) environment of spaceflight provides challenging opportunities for research on sensory-motor adaptation. This paper provides an introduction to the series of interrelated experiments performed on the first Spacelab mission (SL-1) in November 1983 by a team of investigators from MIT and Canada. These investigations, most of which are described in detail in the accompanying five articles, are all aimed at assessing human vestibular and visual responses in space and are intended to clarify the presumed alteration in sensory and motor function in weightlessness. Our working hypothesis, which tied together the various experiments and against which the results are tested, is one of "sensory

reinterpretation." A preliminary report was published previously (Young et al., 1984).

Our experiments were designed to help assess human sensory/motor adaptation to weightlessness and readaptation to earth's gravity, and to simultaneously examine the question: is space sickness a motion sickness? The underlying neuroscience research question is how a fully developed sensory motor system, which receives redundant information from several sensory mechanisms, reorganizes to account for the environmentally imposed change in the relationship between motor commands and sensory feedback. The results of this research relate to classic studies of sensory rearrangement (e.g. Held and Freedman 1963; Rock, 1966; Wallach and Smith, 1972, Wallach and Bacon, 1976) and to recovery from vestibular lesions (e.g. Igarashi et al., 1970; Fregley and Graybiel, 1970). In particular, we ask how pitch and roll perception and postural adjustment are affected by the abnormal pattern of otolith afferent signals which must accompany sustained weightlessness. Our working hypothesis, explained below, was that in the process of sensory adaptation to weightlessness, the low frequency components of the otolith afferent signals (dependent upon head orientation in 1-g) are centrally inhibited or reinterpreted, and that visual and tactile cues consequently play an increasing role in spatial orientation.

Our research also relates directly to the etiology of space sickness, now recognized as a significant problem impacting astronaut performance, safety and well-being. Although space sickness symptoms were not reported in the smaller Mercury and Gemini spacecraft, they have been consistently reported in the Soviet space program (Matsnev et al., 1983) and experienced by Apollo and Skylab crews (Homick and Miller, 1975; Graybiel et al., 1977). The incidence among Shuttle crews has exceeded 50% (Homick et al.,1985). It

has been parsimonious to assume that the genesis of space sickness is similar to that of motion sickness as experienced on earth (e.g. Benson, 1977; Oman, 1982b), although conclusive evidence has been lacking and alternative hypotheses have been suggested (see Oman et al., this issue). The etiology of motion sickness is thought to involve the same physiological mechanisms responsible for spatial orientation and body movement control. Based on a sensory-motor conflict theory (Reason, 1978; Oman, 1982a), motion sickness results when incoming sensory signals no longer match expected patterns learned during previous sensory/motor experience. Because of the environmentally imposed change in graviceptor response to head movements in weightlessness, motion sickness was expected to occur in space. Space sickness would be expected to be exacerbated by real or perceived changes in body orientation, and to subside with a time course paralleling adaptation of sensory-motor systems subserving spatial orientation.

Earlier formal space flight investigations of the influence of weightlessness on human vestibular responses have included the pioneering studies of Graybiel and coworkers (1977) who observed the absence of motion sickness susceptibility to out of plane head movements made in a rotating chair when tested after the fifth day in space. They also showed the ability to maintain a body oriented reference frame in weightlessness. Homick and Reschke (1977) reported postural instabilities with eyes closed following return of the Skylab astronauts to earth. Other tests of inflight postural stability (Clement et al., 1984) and assessment of the vestibuloocular and optokinetic reflexes have been conducted more recently (Thornton et al., 1985; Watt et al., 1985; Vieville et al., 1986). Relevant Soviet research on man in space has largely been limited, until quite recently, to assessment of motion sickness countermeasures, relationship of spatial illusions to symptoms, and

postflight studies of orientation perception, neuromuscular function and ocular counterrolling (e.g Yakovleva et al., 1980; Matsnev et al., 1983). Spacelab-1 provided the opportunity for three teams of experimenters (European Space Agency, NASA Johnson Space Center, and MIT/Canada) to perform extensive tests on vestibular function of the same crewmembers during a mission devoted to scientific goals.

A Sensory Reinterpretation Hypothesis for Adaptation to Weightlessness and Readaptation to One-G.

A sensory reinterpretation hypothesis formed the basis for our proposed experiments and serves as a useful tool for interpreting the results (Young et al., 1976). It assumes that the functionally appropriate physiological adaptation to weightlessness should involve a reinterpretation of afferent signals originating in the graviceptors, particularly in the otolith organs. These receptors act as linear accelerometers, and respond to the physical input of gravitoinertial force. The adequate input to the otolith organs is the force per unit mass or "specific force" ($\underline{f}$), familiar to users of accelerometers for inertial navigation (Fernandez and Macomber, 1962). This force, acting on the otolithic membranes, is equal to the vector sum of gravity ($\underline{g}$) minus linear acceleration ($\underline{a}$). Physically, specific force is the entity tracked by a pendulum. On earth, a non-accelerating body is subject only to the "downward" specific force vector $\underline{g}$, and the pendulum points toward the vertical. In orbital flight, a body which is not accelerating relative to the spacecraft experiences a linear acceleration $\underline{a}$ (as the spacecraft free falls around the earth) equal to the gravitational acceleration $\underline{g}$. The specific force acting on the otolith organs is zero, except when head movements are made. Disregarding small gravity gradient effects, a pendulum in earth

orbit would assume any arbitrary orientation and velocity previously imparted to it, and would be of no use in indicating the direction of the center of the earth, or of the spacecraft floor. The otolith organs, of course, continue to provide the central nervous system (CNS) with afferent signals which are modulated by each head acceleration. We believe that on earth the signals from the saccular as well as the utricular otolith organs serve a dual function in spatial orientation and posture control - to estimate the static orientation of the head with respect to the vertical (the traditional graviceptor function) and also to estimate the linear acceleration of the head during movement. The potential ambiguity in interpretation of otolith signals (tilt vs. acceleration) is presumably resolved by CNS integration of information from the semicircular canals, other orientation senses, and knowledge of commanded motion, based on sensory-motor experience in the prevailing environment. In general, the lower frequency components of the otolith signals indicate the direction of the head relative to gravity, whereas the higher frequency components reflect both head tilt and linear acceleration.

In space, where static head orientation doesn't influence otolith organ afferent activity, each head movement produces a specific force stimulus which can swing rapidly in direction even in the absence of any head tilt. The critical question, for which space experiments are necessary, is whether the CNS adapts to accept a radically new relationship between otolith afferent signals and static and dynamic body movement - as appropriate to the new environment. If such adaptation takes place, its time course and its relationship to space motion sickness become important. The removal of a 1 g bias could, in itself, shift the otolith organs to a new portion of their nonlinear operating range, thereby altering their utility in responding to accelerations. One possibility is that the otolith signals are largely

inhibited, reducing their influence on posture, eye movements and spatial orientation, and consequently leading to a decrease in the ability to sense linear acceleration of even a transient nature. An alternative hypothesis is that otolith signals are reinterpreted as the CNS learns - via sensory-motor interactions with the weightless environment - that the afferent signals now code only linear acceleration. This hypothesis assumes a robust adaptive capacity and is consistent with much previous research on adaptation to other specific sensory rearrangements (reviewed by Welch, 1980). Similar hypotheses have been put forth by other groups (von Baumgarten et al., 1981; Parker et al., 1985). All of our experiments in this program were aimed in one way or another at testing this hypothesis (Oman, 1982; Young, 1983).

Spacelab-1 Mission Operations

Spacelab-1 was the first flight of the Spacelab pressurized module, a 30 foot long, manned laboratory for scientific and technical research developed by the European Space Agency (ESA) and carried into orbit in the cargo bay of the Space Shuttle. The "payload crew" of four, which performed all experiments, consisted of two NASA Astronaut Mission Specialists (one of whom had previous Skylab flight experience) and two Payload Specialists chosen by the investigators from the outside scientific community. One of the Payload Specialists was BKL, a vestibular researcher and bioengineer from our MIT laboratory. The Commander and the Pilot did not participate in flight or pre/post flight experiments. Subjects were male, ranged in age from 35 to 53 years, and were active pilots. They were in good health and were examined and judged normal by our consulting otoneurologist. To preserve anonymity and facilitate data comparison, these subjects are referred to only by letter code A-D throughout this issue. Two crew pairs (A and B, C and D) worked

alternating 12 hour shifts throughout the mission. Crew circadian rhythms were shifted beginning 14 days before launch, with only partial success. After landing, circadian cycles were abruptly shifted back to local time. It was not possible to control for circadian effects in our testing.

During Spacelab missions, the payload crew lives in the Orbiter and works in the Spacelab, commuting via an access tunnel. The laboratory is maintained at normal sea level atmospheric pressure and air composition, and at comfortable temperature and humidity. Conduct of the scientific mission was substantially different from any flown previously. The investigators on the ground and their astronaut colleagues participated in extensive training, simulation and discussion of scientific goals. They performed as an integrated team, facilitated during the mission for the first time by frequent TV coverage and two-way voice communication. This flexibility permitted numerous repairs and adjustments of experiments (Garriott et al., 1984). Despite the flexibility introduced in Spacelab-1 relative to previous missions, the conduct of experiments was severely restricted in comparison to a normal ground laboratory. The competition for crew time, power, communications and other resources, and the relatively short mission duration prevented substantial extension of measurements.

For this first mission, a wide variety of experiments from the U.S., Canada, eleven European countries and Japan were included (Chappell and Knott, 1984). The three closely related sets of vestibular investigations (von Baumgarten, et al., 1984; Reschke, et al., 1984; Young, et al., 1984) required considerable crew flight time and dominated the pre- and postflight testing.

Spacelab-1 was launched on November 28, 1983 and was extended from a planned nine days to a mission lasting 10 days, 8 hours, 47 minutes, with a

landing at Edwards AFB, California. The landing was delayed by eight hours because of computer malfunctions, severely reducing the crew availability for postflight testing on the landing day. The NASA nomenclature used for the flight and preserved in the accompanying articles designates the preflight days relative to launch. "L minus one" (L-1) is the day before launch. Flight days are numbered beginning with zero. Hence Mission Day 1, or MD1, is the second 24 hours in orbit. Postflight days also are numbered from zero (R+1 is one calendar day after the return day). Mission Elapsed Time (MET) is specified in days/hours:minutes since launch.

INSERT FIGURE 1 AND TABLE 1 NEAR HERE

Scope and Interrelationships of the Experiments

The overall scope of our SL-1 experiments and their relationship to the stimuli and outputs of the human system for spatial orientation and balance is indicated in Figure 1. Individual experiments, investigators and SL-1 performances are shown in Table 1. Each experiment examined a different output to reveal some aspect of the way the CNS adapts to the functional equivalent of removing the gravity vector. The "Rotating Dome" experiment explored central integration of conflicting visual/vestibular/tactile sensory cues by measuring roll self-motion and compensatory eye and head movements stimulated by looking into the open end of a rolling drum. The "Rod and Frame" is a pre-post flight test of static visual field dependence. The "Hop and Drop" experiment studied the otolith-spinal reflex which normally prepares one for a landing from a fall. Electromyographic activity from the gastrocnemius and soleus muscles of the leg was measured during footward acceleration provided by stretched elastic cords. The "Position Awareness" experiment measured the influence of weightlessness on both the orientation of perceived objects in the absence of a vertical and the accuracy of pro-

prioceptive cues in determining perceived limb position. The "Space Sickness" investigation clinically characterized space sickness symptoms and studied their relationship to head movements, visual, tactile and proprioceptive cues, and to the shift of body fluids toward the head. A "Posture Platform" and narrow rails were used to measure the postflight degradation of postural stability. The "Sled" is a linear acceleration device which was used for stimulating eye deviation and ocular torsion, as well as subjective motion during horizontal linear acceleration. A rotating chair was used to stimulate the semicircular canals for study of the horizontal vestibulo-ocular reflex and the "dumping" of post-rotatory nystagmus produced by head pitch.

The experiments conducted on Spacelab 1 were the first of a planned series of related investigations, scheduled for continuation and extension on several additional Spacelab missions in the mid-eighties. For operational reasons the experiments originally planned for use with the Space Sled, a controlled linear acceleration device, were postponed until the D-1 Spacelab mission, accomplished in November, 1985. Related tests were performed on the 1984 Shuttle 41-G Mission (Watt et al., 1985).

Preflight testing of the crew for the MIT/Canadian experiments was conducted from 1979 through 1983 at the experimenters' laboratories (MIT, McGill, DCIEM/Toronto) and at NASA's Johnson Space Center, Kennedy Space Center, and Dryden Flight Research Facility (DFRF). Of particular value for protocol development, training and baseline data collection were the series of four sets of parabolic flight tests producing repeated 20-25 sec periods of weightlessness in NASA's KC-135 aircraft. Preflight and postflight testing by all life science experimenters was conducted at an especially constructed Baseline Data Collection Facility at DFRF at approximately 152, 122, 65, 44 and 10 days before launch. Subjects A and B were tested within hours of

landing, and all four subjects were tested on 1,2, 4 and 6 days after return. Parabolic flights to assess 0 g motion sickness susceptibility and reorientation illusions were performed preflight, and three days, and one year after landing.

Results and Discussion

The results of our experiments on Spacelab 1, discussed in detail in the accompanying papers, must be interpreted cautiously because the experiments were conducted on only 2-4 subjects, and with fewer repetitions and frequently under less well controlled conditions than desired. These results, when taken together with findings from other related experiments, appear generally consistent with the sensory reinterpretation notion. We are aware of no evidence pointing to pathological alteration of sensory function at the end organ.

Early in the SL-1 flight 3 of 4 subjects developed space sickness symptoms, which largely resembled those of prolonged motion sickness, superimposed on the effects of fluid shift towards the head. Symptoms abated after 2-3 days. Short duration preflight motion sickness susceptibility tests did not predict in-flight sickness intensity. However, head movements, especially in pitch, as well as visual and tactile cues to orientation, influenced symptom level in ways consistent with the sensory conflict theory for motion sickness and with the hypothesis of sensory reinterpretation.

Changes in sensory-motor function were observed both during the flight and extensively following the landing. Otolith-spinal reflex responses to footward acceleration with head erect were inhibited when tested early in the flight, and declined further during the week in weightlessness. However, in the tests performed several hours after landing the otolith-spinal reflex

had returned to preflight levels. Similarly, the short latency reflex reactions to destabilization of standing on the posture platform were unchanged post flight, although the longer latency responses demonstrated postural instability, with eyes closed, on both the platform and on the rails tests. The Rotating Dome experiment data suggest increased weighting of visual cues and tactile cues, and reduced influence of graviceptor signals in determination of orientation in weightlessness. Postflight measurements also suggested a slight increase in static visual field dependence. Proprioception may have been degraded in flight. Postflight reaction to horizontal linear acceleration revealed a reduction in dynamic ocular counterrolling, and increased variability in the detection of low level accelerations, but an enhanced ability to use suprathreshold acceleration cues to null lateral position in a closed loop, non-visual, tracking task.

INSERT FIGURE 2 NEAR HERE

As illustrated in Figure 2, the human estimation of body position and postural reactions is thought to change in weightlessness to make use of the varied sensory inputs in a manner which is fundamentally appropriate to the microgravity condition. In particular, it appears likely that at least three separate aspects of such reinterpretation may be present: tilt acceleration reinterpretation, reduced postural response to z-axis linear acceleration, and increased attention to visual cues. In the course of the reinterpretation, motion sickness symptoms, caused by the original sensory motor conflicts, gradually disappear.

As illustrated in Fig. 2a, for preflight spatial orientation, the subject relies heavily on the static gravitoinertial vector for his perception of the vertical, which can be displaced by a low frequency acceleration (e.g. Mach, 1875; Howard and Templeton, 1966; Schoene, 1980; Young, 1984.). However,

each individual has his perception of the upright influenced, to varying degrees, by the presence of elements in the visual field, especially those normally associated with the vertical (e.g. Witkin, 1958; Howard, 1982) and by localized tactile cues such as pressure on the soles of the feet. Moving visual scenes (not shown in the figure) can also create a sense of body self-motion. Furthermore, each individual has a tendency to align the perceived vertical toward the head or feet along the torso long axis. This tendency is represented by an ideocentric body axis vector and is assumed to vary in strength among individuals (Mittelstaedt, 1983).

These sensory vectors must be reinterpreted for spatial orientation in weightlessness. As shown in Fig. 2b, the gravitoinertial vector now is merely the opposite of linear acceleration relative to the spacecraft. If it were to continue to dominate the perception of tilt orientation, the astronauts would experience 180 degrees of roll or pitch each time they accelerated and decelerated while translating through the spacecraft, which was never reported. Instead, we believe that the signals from the graviceptors are reinterpreted to represent linear translation, as required for locomotion accuracy in space, and as carried over to the post flight closed loop acceleration nulling tests. In-flight postural reaction to changes in acceleration, at least along the body z-axis (Watt et al, this issue; Reschke et al., this issue) show a decrease in sensitivity, which is consistent with the absence of a need to prepare the "anti-gravity muscles" for a fall (It remains to be determined whether this inhibition is limited to z-axis acceleration.). Upon return to earth this reinterpretation of graviceptor cues leads to a decreased ability to stand up with eyes closed, except within a very narrow cone of static stability near the upright. Actual head tilt may be perceived as a lesser tilt post flight, combined with linear

acceleration in the opposite direction, leading to destabilizing postural reactions in the wrong direction. Postflight changes in postural control strategy may be related to this tilt/translation reinterpretation (Kenyon and Young, this issue, Reschke et al., 1984). Ocular counterrolling, which is a normal compensatory response to a tilted gravitoinertial vector, is also shown to be reduced post flight dynamically (Arrott and Young, this issue) and statically (von Baumgarten et al., 1984; Parker et al., 1985; but not Yakovleva et al., 1980). Post-flight perceived tilt, in the dark, is reduced (Benson et al., 1984) as predicted by the hypothesized carry-over of the otolith reinterpretation, and dynamic tilt was reported on other crews to lead to a strong translation sensation (Parker et al., 1985, who independently arrived at a similar otolith tilt/translation reinterpretation hypothesis.)

In the absence of usable graviceptor information regarding body orientation in weightlessness, the nervous system must pay increased attention to the remaining sensory orientation signals. Subjective reports from crew members indicate large variations in individual styles, but never a prolonged sense of absence of a reference frame or "disorientation". The increased length of the "visual" vector in Figure 2b is intended to represent the increased weighting given to dynamic visual inputs to self motion (the dome experiment) and to static elements such as the floor or ceiling, another crew member, or the earth (Oman et al., this issue). In many cases the relative weighting may be a complete domination by the visual, body control or tactile vector in weightlessness. Large individual differences in visual field influence in weightlessness are reflected in the post flight increases in field dependence. Similarly, localized tactile cues, such as pressure on the feet in the Dome and the Hop/Drop experiments or on the buttocks and

back when wedging into a corner, serve to take on an increasing role in determining spatial orientation and a sense of well-being. Finally, the influence of the postulated body-axis orientation vector, which could allow some crew members to orient their reference frame to their body long axis in weightlessness, is greater than pre-flight because of the reinterpretation of the graviceptor cues.

FIGURE LEGENDS

Fig. 1 Scope of the MIT/Canadian Spacelab 1 experiments, by experiment short name, relative to a schematic representation of the role of the vestibular and other senses in control of posture, eye movements and perception of orientation. Experiment short names are keyed to Table 1.

Fig. 2 Schematic representation of the sensory vectors which are used in determining human spatial orientation. In Fig.2a, the subjective zenith is arrived at by a vector sum of the various sensory contributions, but is dominated by the gravitoinertial vector (f). If the subject, shown standing on a moving wagon, were not accelerating, this would indeed be vertical (g). The subjective vertical is also biased slightly by the influence of vertical or horizontal elements in the visual field (v), by localized tactile cues (t), and by one's own body axis (m). The strength of these other cues depends on the individual. In Fig. 2b, which represents the similar situation in weightlessness, the crucial difference is that the gravitoinertial vector now represents only linear acceleration (a). The subjective zenith, or local reference axis if "up" has lost all meaning, now ignores the gravitoinertial vector in favor of the stronger visual, tactile and body centered axes. Tactile cues normal to support surfaces, such as illustrated in fig. 2b, could be developed by a loading mechanism such as stretched elastic cords (not shown) or briefly by extension of the legs. Differences among the individual crew members in the relative strength of these vectors is reflected in the range of orientation styles.

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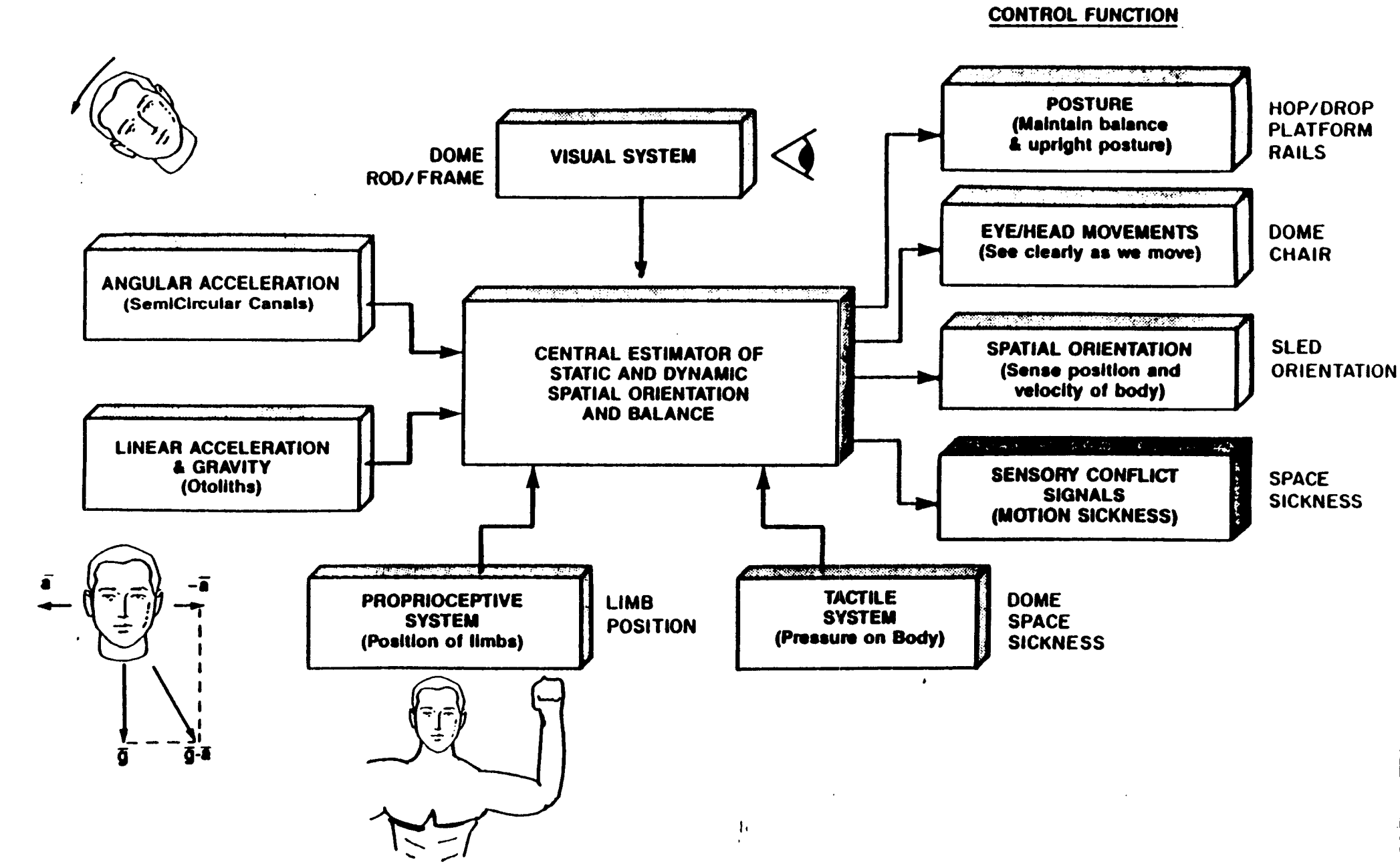
TABLE 1: MIT/Canadian Vestibular Experiments on SL-1

Experiment	Lead Investigator	When Performed
1. Visual-Vestibular Interaction (Dome)	Young	Subj. A,B, MD 1,2,4,5,6,7 Subj. C,D, MD 1 (failed)3,6
2. Otolith-Spinal Reflex (Hop/Drop)	Watt	Subj. A, MD 0,1,6 B, MD 0,1,6,7
3. Awareness of Orientation and Limb Position	Money	*Subj. B, MD 1 *Subj. C, MD 8
4. Posture Control (Platform/Rails)	Kenyon	Pre-Postflight
5. Motion sickness susceptibility (Space Sickness)	Oman	Subj. A,B,C,D continuous
6. Perception of Linear Acceleration (Sled)	Arrott	Pre-Postflight (sled scheduled for D-1)
7. Ocular torsion during lateral acceleration	Young	**Subj. C,D, MD0, MD7
8. Vestibulo-ocular reflex Nystagmus Dumping (Chair)	Oman	*Subj. A,B, MD 7 *Subj. C, MD 3,6

All in-flight tests were also performed pre and post flight.
MD: Mission Day
* Data still being analyzed - not reported in this Issue
**No flight data available due to equipment failure. Full test scheduled for D-1. Pre-postflight data reported with expt. 6.


CONTROL FUNCTION
DOME
ROD/FRAME
VISUAL SYSTEM
ANGULAR ACCELERATION
(SemiCircular Canals)
LINEAR ACCELERATION
& GRAVITY
(Otoliths)
CENTRAL ESTIMATOR OF
STATIC AND DYNAMIC
SPATIAL ORIENTATION
AND BALANCE
POSTURE
(Maintain balance
& upright posture)
HOP/DROP
PLATFORM
RAILS
EYE/HEAD MOVEMENTS
(See clearly as we move)
DOME
CHAIR
SPATIAL ORIENTATION
(Sense position and
velocity of body)
SLED
ORIENTATION
SENSORY CONFLICT
SIGNALS
(MOTION SICKNESS)
SPACE
SICKNESS
PROPRIOCEPTIVE
SYSTEM
(Position of limbs)
LIMB
POSITION
TACTILE
SYSTEM
(Pressure on Body)
DOME
SPACE
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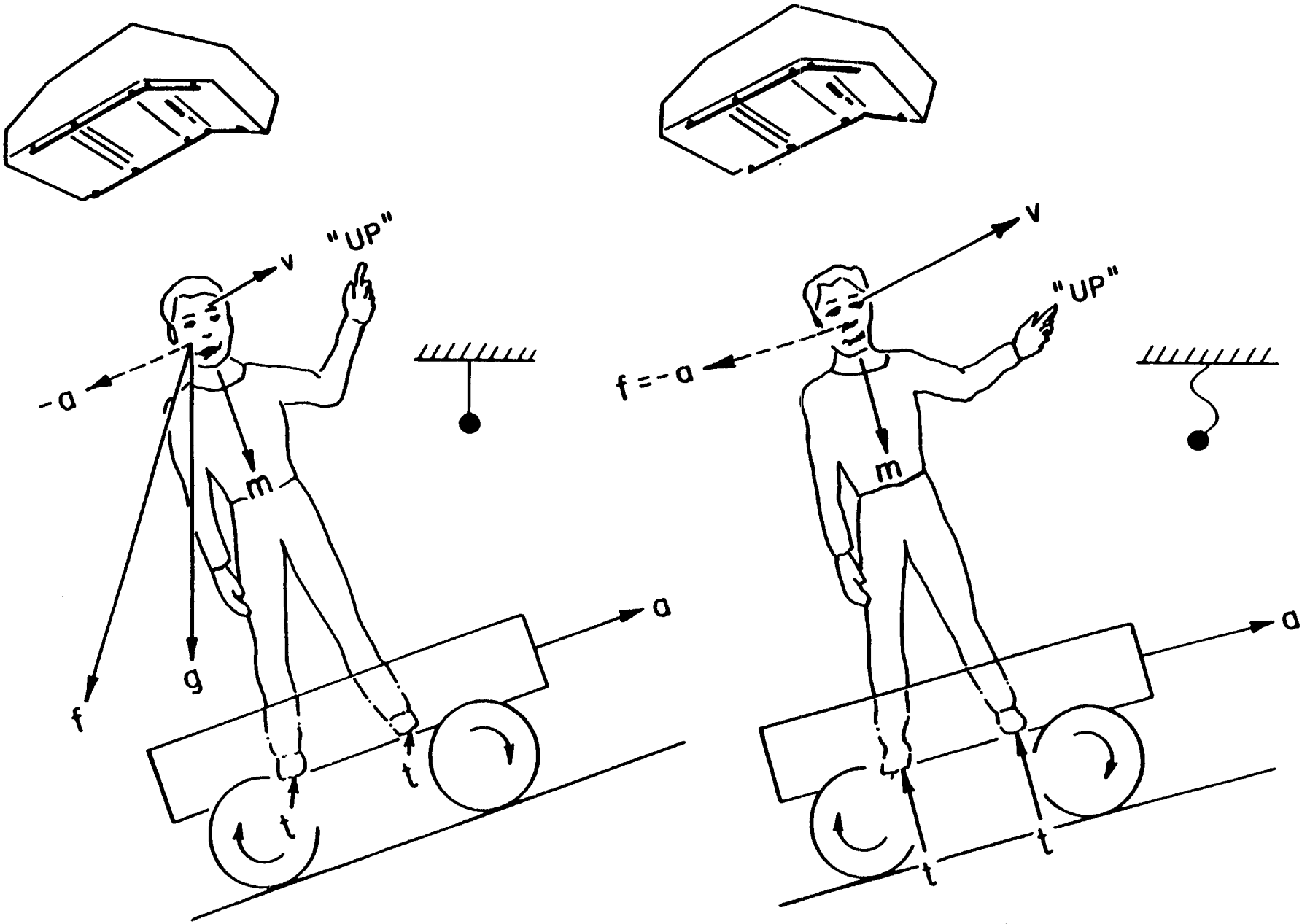

a. PRE-FLIGHT ORIENTATION VECTORS.

b. IN-FLIGHT ORIENTATION VECTORS

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26p

VISUAL VESTIBULAR TILT INTERACTION IN WEIGHTLESSNESS: MIT/CANADIAN VESTIBULAR EXPERIMENTS IN SPACELAB-1. PART 2.

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Key words: Vestibular, visual vestibular interaction, space, vection

SUMMARY

Adaptation to weightlessness includes the substitution of other sensory signals for the no longer appropriate graviceptor information concerning static spatial orientation. Visual-vestibular interaction producing roll circular-vection was studied in weightlessness to assess the influence of otolith cues on spatial orientation. Preliminary results from four subjects tested on Spacelab-1 indicate that visual orientation effects were stronger in weightlessness than preflight. The rod and frame test of visual field dependence showed a weak postflight increase in visual influence. Localized tactile cues applied to the feet in space reduced subjective vection strength.

INTRODUCTION

The visual-vestibular interaction experiments on Spacelab-1 examine the proposition that on earth the gravitational field acting on human graviceptors, including the otolith organs, inhibits the development of visually induced self-motion. In weightlessness, this inhibition should therefore be reduced. The "rotating dome" visual-vestibular interaction experiment is carried out with the head held stationary by a biteboard and deliberately eliminates stimulation of the vestibular organs. It is precisely this lack of vestibular stimulation, and the consequent absence of vestibular signals

to confirm or deny the visual illusion of self-motion, which is at the heart of this investigation.

The underlying phenomenon of visually induced self-motion, or "vection", is the well-known illusion of self-motion which occurs when a large visual field is moving relative to a stationary observer. These illusions require a wide field of view, homogeneously moving field with sufficient number of contours (Held et al., 1975; Young, 1981, 1983).

Human reactions to viewing a homogeneous large visual field rotating about an earth horizontal axis are rather complex and surprising. Normally, a subject standing erect and fixating upon the axis of a uniformly rotating vertical disk begins to experience visually induced roll and tilt as illustrated schematically in Figure 1 (Fischer and Kornmüller, 1930; Dichgans et al., 1972). The tilt is usually experienced as a combination of two conflicting phenomena, referred to as "paradoxical vection". This is a sensation of continuous self-rotation about the horizontal axis, but a limited, somewhat steady, angle of tilt. Only rarely, in these circumstances, does the subject indicate complete unambiguous self-rotation with a sensation of rotating fully through an upside-down orientation in the laboratory. The perception of tilt angle is manifest in several ways. Postural stabilization reactions, which we term "pseudo-vestibulocollic" reactions, result in head and trunk tilt in the direction of the rotating field. If the subject attempts to align a small, foveally centered rod with the perceived vertical, he tilts it 5 to 30 degrees in the direction of field rotation, reflecting his perception of body tilt in the opposite direction (Dichgans et al., 1972). The limited visually induced tilt, as opposed to continuous self-rotation, may be attributable to the action of gravity on the graviceptors.

In addition to inertial signals detected by the vestibular system which

may enhance or diminish visually induced motion, other non-visual cues can play an important part in self-motion perception. Auditory signals (Lackner and Levine, 1979), kinesthetic movement (Brandt et al., 1977) and self-generated motion (Bles and Kapteyn, 1977) all enhance the illusion of self-motion and influence the interpretation of a moving visual field. Localized tactile or pressure cues, which are normally of maximum magnitude directly under the subject, can also influence self-motion. Although inertial forces act on various parts of the body, the otolith organs play the primary role in human orientation to the gravitoinertial vertical (Graybiel, 1974). In paradoxical vection, indication of the inertial vertical by the otolith organs is in conflict with any visually induced sense of rotation about a horizontal axis. The lack of complete suppression of visually induced tilt speaks to limits to the strength of this otolith inhibition, even in 1 g. The effectiveness of graviceptor cues on the perception of the vertical is known to decrease when the head is tilted in roll away from the erect position (Schöne and Udo de Haes, 1971). We attribute this phenomenon to reliance principally on the signals from the utricular otolith organ to determine head orientation (Young et al., 1975) and to the fact that this organ's sensitivity to changes in head tilt decreases as the cosine of the angle of the head longitudinal axis from the vertical (Ormsby and Young, 1976). Furthermore, the inhibition of visually induced static tilt, based upon viewing of static tilted visual scenes, also decreases when the head is moved away from the vertical (Udo de Haes, 1970). Visually induced tilt is increased, relative to the head erect position, when the head is placed on the side or inverted and is minimized when the head is pitched 25 degrees forward, a position which is theoretically optimum from the point of view of placement of the utricular organ in a position to be maximally sensitive to head tilt (Young et al., 1975).

With the subject lying supine and viewing the field above him rotating about an earth vertical axis, the perception of paradoxical vection is generally replaced by a sensation of continuous self-rotation about a vertical axis after a characteristic onset latency, intermittently interrupted by unexplained losses of vection ("dropouts"). The onset latency and gradual buildup have been attributed to visual-semicircular canal conflict (Zacharias and Young, 1981), but may also involve otolith function. In this case, since gravity is parallel to the field rotation axis, graviceptive cues are present, but would not be expected to limit the extent of rotation. However, tactile cues indicate a definite orientation and the failure of them to confirm roll angular or centripetal acceleration may inhibit the perception of circularvection.

Two primary effects on vection are expected from long-term weightlessness. First, since graviceptor cues are no longer present to inhibit circularvection, it is expected that vection will be more intense and possibly have a faster onset than in the ground erect position. In preparation for the Spacelab experiments, brief tests of visually induced self-motion were carried out during the 25 second "free-fall" portion of parabolic flight in NASA's KC-135 aircraft. In this situation, many subjects experienced strong and rapid self-rotation during "zero-g", sometimes paradoxical, but often continuous. The dome speed range of 30 to 60 deg/sec was found to be adequate to produce some vection in all crew members. When attempts were made to produce localized tactile loading of the feet, either by asking the subject to actively press against a footrest or by the use of stretched elastic cords to pull the subject onto the floor of the aircraft during zero-g, the visually induced self-motion in the KC-135 was frequently limited in amplitude, its onset was delayed, and it was qualitatively less compelling (Young et al., 1982).

These earlier experimental results led to the expectation that, in space, the absence of steady gravitoinertial forces to inhibit circularvection would produce an immediate strengthening of visually induced self-motion relative to the ground erect tests, reflecting the absence of an inhibiting otolith cue. It is further proposed that circularvection intensity will also be increased and latency decreased relative to the ground supine tests. This effect is presumed to occur as the brain "learns" to rely less on ambiguous vestibular cues and more on visual cues for orientation.

Ocular torsion is another phenomenon associated with large field optokinetic stimulation and visually induced tilt. It was measured in our Spacelab experiments, but the results are not presented in the current paper.

The inflight experiments on visual vestibular interaction on Spacelab-1 consisted of early and late mission tests of circularvection, posture and ocular torsion, using a "rotating dome" apparatus (see Methods) with and without localized tactile cues. The rotating dome experiments were also performed pre and postflight in both the subject erect and subject supine orientations.

A complementary static measurement of visual vestibular interaction is afforded by the "rod and frame" test (Witkin, 1959). This test measures visual field dependence by subjective indication of tilt of the perceived vertical as influenced by a tilted visual framework. This simple test has been shown to demonstrate the same individual characteristics of field dependence as the more complex "tilted room" experiments, which seems more akin to the Spacelab orientation situation (Asch and Witkin, 1948). The rod and frame experiment was only performed before and after the mission. Its purpose was to determine if the putative increased dependence on static visual cues for orientation in space would carry over postflight.

METHODS

The moving visual stimulus was provided by a roughly hemispherical "rotating dome" filling the subject's field of view. When the subject's head was rigidly held on the center line of the dome by a fitted acrylic biteboard, nothing except the interior of the dome was visible to the subject. The distances of the visual surface ranged from 34 cm straight ahead to 17-20 cm laterally and vertically from the mean eye position. The visible surface of the dome was white and covered with randomly positioned colored dots, 1.9 cm in diameter. The choice of size and density (approximately 800 per square meter) was dictated by earlier studies on visual field parameters and their effects on circularvection (Held et al., 1975) and were validated in parabolic flight. In the center of the dome, along the axis of rotation, was a hole, 9 cm in diameter, in front of which a 7.62 cm long and 11.43 cm diameter sleeve protruded to concentrate a photo flash. This hole accommodated a lens for recording of ocular torsion of the left eye. Although the lens was circularly symmetric, the ring flash surrounding it had a noticeable reference point on the tube. This point and printing on the lens sometimes appeared to rotate at the onset of vection and served to assist some subjects in judging their onset of perceived self-rotation.

Each experimental run consisted of a series of six trials. For each trial, the dome rotated at a constant angular velocity of 30, 45 or 60 deg/sec clockwise or counterclockwise for a period of 50 seconds, followed by a 10 second stationary pause separating the trials. Two separate sequences of trials, each with randomized speed and direction, were utilized in this study. Subjects used a spring restrained rotary knob "joystick" for subjective estimation of perceived self-rotation. They were instructed to deflect the

joystick in the direction of their own perceived self-motion regardless of the qualitative nature of that self-motion. If and when the rotating visual field appeared to be stationary in space, implying that the subjective sense of self-rotation was at a velocity equal to that of the dome, the subjects indicated this "saturated vection" by full deflection of the joystick. Partial vection was indicated by a proportional joystick movement. Because of the extensive preflight data collection, subjects were well-versed and self-consistent in vection indication by subjective scaling and in the meaning of the various terms applied to the qualitative nature of the sensation. At the end of each run, subjects were requested to describe the subjective nature of any vection perceived during the preceding run.

Body sway in flight was recorded by use of a Spacelab closed circuit TV camera with a back view of the subject and the rotating dome. Body sway angle was calculated from video tapes by alignment of a protractor with the subject's back. Each angular increment of approximately 2 degrees was recorded. The ocular torsion measurement method involving flash photography failed in its first attempted use in flight and all of the flight experiments were carried out using a substitute video camera with the same lens but without the flash. To control for the influence of flash episodes on vection, all postflight measures were taken in pairs of runs, with one performed with flash photography and the other with video. All preflight tests utilized flash photography.

In order to produce tactile and proprioceptive forces on the legs, trunk and feet inflight, we made use of the bungee cord shoulder harness system developed by Watt for his otolith-spinal reflex experiments on the same flight (Watt and Money, 1986). When the subject stood upright with the three stretched elastic cords from each side of his harness connected to

hooks beside his feet on the floor, an upward force on the feet of approximately 50-75% of body weight was produced. (The actual force level was not considered critical.) The counterforce, taken up by the harness, was distributed relatively evenly over the hips and shoulders. There were no reports of subjective sensations of localized force, except on the feet, when the harness was tested in "zero-g" parabolic airplane flight.

Insert Table 1 near here

Each experimental flight session consisted of two runs for each subject, one with bungee cords and one without. Subjects performed the experiments in pairs. The original balanced experimental design was changed by operational factors associated with adjustments required by a change to TV recording of torsion. The actual performances are listed in Table 1. Digitized data representing dome speed and joystick deflection were encoded and transmitted to the ground either during the experiment or shortly thereafter. Several runs were lost as a result of data transmission technical difficulties. Subjective estimation parameters were calculated by computer processing of the joystick data. The onset latency was defined as the time from the beginning of dome rotation until the first deflection of the joystick by more than 10% of its full scale range for at least one second. The average vection intensity indication was calculated as the average joystick deflection (relative to full scale) over the 50 second dome trial.

The pre and postflight rod and frame tests of static field dependence followed the method of Asch and Witkin (1948). Subjects were seated in a hard upright chair in a dark room and viewed a dimly lit frame with sides 107 cm long by 2.5 cm wide surrounding a rod 99 cm long and 2.5 cm wide, located 180 cm from the subject. This frame was tilted to 28 degrees in either direction from the upright. Subjects told the experimenter to rotate the rod about a central axis until the subject judged it to be vertical.

Angular deviation of the rod was measured by a potentiometer, and constituted the determination of field dependence. During each experimental session, four measurements were taken in each direction, as well as two control measurements without the frame. Means and standard deviations were calculated for each subject in each direction of frame tilt. In addition, the Embedded Figures Test, which is also reputed to measure field dependence, was administered to the crew once, four years preflight (Witkin et al., 1971).

RESULTS

Subjective Reports

All subjects' comments indicated an increased visual dependence for orientation inflight, with an enhanced effect late in the flight. Large individual differences in preflight sensations were also reflected during the inflight tests. Localized tactile cues reduced the visual effect in various ways early in the flight, but had less of an effect late in flight. All subjects reported stronger and more rapidly occurring vection when they experimented with the head free of the biteboard in front of the rotating dome after the normal protocol on MD4 (Mission Day 4) (subjects A and B) and on MD6 (subjects C and D). Only one subject (D) reported continuing vection following eye closure. These comments are summarized in Table 2.

Vection Indications

To measure the effects of weightlessness on the sensation of vection, statistical tests of the time from start of dome rotation to onset of vection were performed. For each subject, each preflight dome run (consisting of six trials) was compared with each inflight free-floating dome run. The paired t-test was used, with the six stimulus conditions paired for each run comparison.

The complete onset time data set for Subject A, preflight and inflight, is given in Table 3 and consists of five free-floating runs in flight and 20 preflight runs (10 upright and 10 supine). Thus a total of 20 x 5 = 100 comparisons of six trials each were made. Seven of these comparisons did not contain enough data pairings (due to missing data) to yield a valid statistical test. Of the remaining 93 tests, 75 had preflight mean onset time longer than the inflight mean. Fifty-nine of these were significant at the 80% level or higher, while only forty-one were significant at the 90% level or above. In particular, of the 59 tests at 80% or above, 39 were for comparisons with the upright and 20 for comparisons with the supine preflight test. Similarly, of the 41 tests at or above 90% significance, 28 were for upright and 13 for supine.

Similarly, for Subject B, 99 comparisons were performed, of which 78 indicated preflight mean onset latencies greater than inflight. Sixty-one comparisons were at the 80% significance level or above (twenty upright and forty-one supine). At the 90% level, there were 45 comparisons showing inflight latencies shorter than preflight (14 upright and 31 supine).

Subject C gave more ambiguous results. Of 40 comparisons (two inflight free-float runs), only 19 indicated a preflight mean latency greater than inflight. For comparisons of only Mission Day 3 data to preflight, however, 15 of 20 comparisons indicated a larger preflight mean (six at 80%, three at 90% significance). Six of the larger preflight mean results were for upright tests and nine were for supine. Conversely, comparing Mission Day 5 to preflight gave only 4 of 20 comparisons in which the preflight mean was larger (none as high as the 80% level).

Finally, Subject D had 33 of 40 tests for which the preflight mean was greater than inflight (25 at 80%, 9 at 90%). Of these 33, 18 were with

upright conditions and 15 with supine.

Despite the uniform comments that the bungee-cord-induced localized tactile cues inhibited vection in flight, neither average vection intensity nor average onset latency supported the subjective reports with statistically significant results. For seven of the eleven inflight comparisons, the average onset latency for a six trial dome run was longer when tactile cues were applied. Only 27 of the 47 individual trial comparisons produced weaker average vection intensity with tactile cues than for the free-floating conditions.

Insert Figure 2 near here

When all trials were combined for each subject in a give test run, the variability in vection onset time became too large to permit statistically significant conclusions. Nevertheless, certain trends were evident, as seen in Figure 2. The inflight mean onset times were generally lower than preflight, as were the postflight onset times.

Body Sway

Rear-view video images of the subjects during all the flight experiments revealed considerable body sway during the free-float dome run only for subject D on the seventh day of flight. Body sway for clockwise dome rotations is counterclockwise, corresponding to contraction of right neck muscles due to a head-righting reflex which would tend to orient the head to the displaced visual vertical. Sway for counterclockwise dome rotations is in the opposite direction.

ROD AND FRAME

Three of the subjects were field independent, with average deviations of the rod toward the frame of less than the 6 degree average of the normal male population (Witkin and Asch, 1948; Mansueto and Adevai, 1967). The

Insert Figure 3 near here

rankings of the subjects in order of increasing field dependence preflight was B, C, D, A. The raw rod and frame data shows high variability, but there is a trend toward increased postflight field dependence with lasts for several days postflight. The most dramatic effects were seen on the first tests postflight on the landing day and the following day. Figure 3 is a comparison of the average rod deviation during all of the preflight sessions with those taken during the first two days back on earth. Each of the four subjects shows an increase in visual field dependence following the flight. Table 4 gives the average deviations to the left and right separately for each subject. Note the marked asymmetry of subject A's postflight responses to different directions of frame tilt. Because of the large variance in these measurements, only subjects A ($p < 0.001$) and B ($p < 0.01$) showed statistically significant increases postflight. The Embedded Figures Test, administered preflight, measures the speed with which a subject can identify simple figures hidden within more complex ones and is also construed as a measure of field dependence. All subjects were quicker than the published population norm of 50 seconds for adult males, indicating field independence. Rankings in terms of speed of identification were D (3.5 seconds), C (10.8 seconds), A (16.4 seconds), and B (18.7 seconds).

DISCUSSION

We believe that, in the absence of a static gravitoinertial force during weightlessness, visual orientation cues become stronger than on earth and that this visual contribution carries over to after the flight. Although the semicircular canal organs still presumably deny the existence of rapid self-rotation accelerations, the otolith organs no longer deny or confirm the existence of continuous rolling motion. As expected, the measured difference

between preflight and inflight was greater for the preflight erect than for the preflight supine tests, since in the latter situation the influence of the graviceptors on roll orientation was minimized. The limited data and absence of very early inflight tests does not permit any conclusions concerning the time course of development of the visual dominance inflight. Despite individual differences, each of the four test subjects reported subjectively stronger vection during the Spacelab experiments than during the supine or erect ground-based tests, each qualitatively maintaining his individual stereotypical reaction.[1]

Perhaps the most surprising aspect of the development of circularvection inflight was that it was not completely saturated for all subjects. After all, in the absence of otolith conflict and tactile or gravitoinertial cues, and after several seconds for semicircular canal influences to die out, what permitted the subject to resolve the moving visual field in favor of dome rotation, rather than complete self-rotation? Although saturated vection was reported by some subjects at some times, it clearly was not ubiquitous. In the case of the supine preflight tests, the lack of saturation was attributed to mental set and to the substantial tactile information present. Perhaps the residual tactile information from the teeth clenching on the biteboard during the flight was sufficient to produce some cues which did not support the perception of acceleration to constant high speed self-motion velocity. Indeed, in a few informal observations tried in flight by each of the four subjects with the head removed from the biteboard, the vection appeared to be stronger and was brought on more rapidly with head roll, but it was still not totally saturated. In the absence of tactile or gravito-

[1]Subsequent testing of five subjects on the D-1 Spacelab mission in November 1985 uniformly supported this finding.

inertial cues to deny rotation, and without signals from the semicircular canals to confirm deceleration, a continuation of the pre-existing vection with eye closure might have been anticipated in zero g, but was only reported as a brief effect by one subject.

The influence of tactile cues, as applied by localized pressure to the feet through stretched bungee cords, was, subjectively, inhibitory to vection although this was not supported by quantitative measures of vection. To a certain extent, localized tactile cues appeared to play a role concerning localized self-orientation normally provided by the otolith organs. The subjective reports were variable. Some subjects felt paradoxical vection with the applied tactile cues (just as they did when standing erect in 1-g). This implies a rather complete substitution of tactile for otolith information or increased weighting of tactile information in weightlessness. For others, the presence of the tactile cues merely slowed down the vection.

The carry-over of the hypothesized increased influence of visual cues on orientation after the flight was supported, although not proven, by both the rotating dome onset latencies and the rod and frame visual field dependence measurements. Increased postflight visual influence on perceived vertical was also found by von Baumgarten and coworkers (1984) using an independent vection test on subjects C and D.

Vection susceptibility did not correlate with static field dependence as measured by the rod and frame test. Subject A, who was the most resistant to vection, was most influenced by the visual surround in the rod and frame test and experienced the largest increase in field dependence postflight. Subject D, who experienced full saturated vection for the first time during the flight, and who was judged extremely visually dependent in flight based on his comments on the strength of local visual references in determining his

orientation, also showed a significant increase in field dependence postflight.

Comments from some of the subjects indicated qualitative differences between preflight and postflight dome responses. Subject B, for example, reported that during the erect rotating dome experiment on the day of landing, he suddenly felt himself pitched forward 90 degrees and rotating about an earth vertical axis. This observation, which resolves the otolith-optokinetic conflict, has occasionally been reported by others in ground-based testing and had never been noticed by this subject prior to R+0. The possibility of a conditioning effect due to previous testing cannot be dismissed.

Despite the small number of test subjects and high variability, the experimental results support the notion that dynamic and static visual cues play an increasing role in spatial orientation in weightlessness, and that vestibular inhibition of vection is reduced. This adaptation represents one important part of a more general sensory-motor reinterpretation associated with adaptation to weightlessness (Young et al., this issue).

CONCLUSIONS

Subjective comments indicated generally increased reliance on visual cues for orientation inflight versus pre and postflight, supported by shorter latency vection inflight. Tactile cues had a subjective effect on inhibiting vection by substituting for gravity cues. Increased postflight visual dependence was suggested by both the rotating dome and the rod and frame tests.

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FIGURE LEGENDS

Figure 1. Schematic drawing showing reactions to rotating dome. As the spotted dome rotates clockwise (from this view), the subject begins to feel that the dome slows or stops and that he is tilting counterclockwise, which he indicates by turning the indicator knob. This tilting sensation causes a vestibulo-collic reflex which attempts to bring the head back (clockwise). Since the head is actually held stationary by the biteboard assembly, the neck torque produces a counterclockwise rotation of the trunk. Torsional eye movements follow the dome with smooth slow phases of optokinetic nystagmus clockwise. The slow compensatory torsion is also in the direction to compensate for the visually induced tilt.

Figure 2. Roll vection onset time - the latency from the beginning of dome rotation to the development of sustained self motion of at least 10% of saturation. Note the different ordinate scale for each subject. All dome speeds and both directions averaged for each test day. Vertical lines represent one standard deviation each session. Tactile cue (bungee cord) runs are separated from free float runs in flight (o = free float, x = tactile). Mission day 1 is the second day of the flight.

Figure 3. Bar graph showing average performance on the rod and frame test preflight, compared to R+0 and R+1 performance. See Table 4 for standard deviations and separate directions.

Table 1
Dome test sessions performed during the flight of Spacelab-1

	Subject A	Subject B	Subject C	Subject D
MD1	F DR1 1/20:05 T DR2 **	F DR4 1/08:24 T DR3 **		
MD2	F DR1 1/23:57 T DR2 2/00:26	F DR4 2/00:06 T DR3 2/00:19*		
MD3			F DR4 3/20:54* T DR3 3/20:47*	F DR1 3/20:25 T DR2 3/20:35
MD4	F DR1 4/07:43* T DR2 4/08:09	F DR4 4/07:56 T DR3 4/08:22		
MD5	F DR1 5/04:51 T DR2 **	F DR4 5/04:59* T DR3 5/05:22*		
MD6			F DR1 6/12:25 T DR2 6/12:39	F DR4 6/12:59 T DR3 6/12:52
MD7	F DR1 6/23:46 T DR2 7/00:12	F DR4 6/23:57 T DR3 **		

F = free-floating: restrained only by biteboard and joystick
T = tactile: restrained by harness and stretched elastic cords

*Data partially unavailable for analysis
**Data not transmitted or not analyzable, or planned test not performed.

Table 2. Summary of Subject Comments

Subject A:	Flight experiment similar to ground. No sense of self-rotation. Tactile cues had little effect. Vection stopped immediately on eye closure.
Subject B:	Complete unsaturated roll sensation. Tactile cue effect: like standing, still complete roll, not a phantom vertical, not paradoxical vection. Tactile cues more effective early than late. Vection stopped immediately on eye closure.
Subject C:	Full continuous roll sensation. Tactile cue effect: no conflict, entire Spacelab seems to roll with subject. Early tactile cues made vection more difficult. Late tactile cues had no effect. Vection stopped immediately on eye closure.
Subject D:	Steady continuous roll sensation. Tactile cue effect: paradoxical vection, similar to ground erect. Vection decayed 2-3 seconds after eye closure.

TABLE 3. Preflight and inflight onset time for Subject A.

PREFLIGHT ONSET TIME - UPRIGHT

	F-90		F-60		F-30		F-11		F-10	
	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2
30/CW	2.12	3.66	3.12	2.66	3.40	**	2.01	1.54	2.93	7.23
45/CW	2.14	1.67	2.37	2.15	2.46	3.83	1.32	2.13	2.53	1.49
60/CW	2.00	1.33	2.89	1.99	1.48	**	1.65	2.94	2.19	2.46
30/CCW	5.81	1.94	6.48	2.80	1.97	4.34	1.86	4.01	1.39	1.39
45/CCW	1.91	0.02	0.78	2.50	2.73	**	3.28	3.82	1.13	2.83
60/CCW	4.28	2.57	3.26	4.73	1.73	**	3.06	3.18	1.85	3.35

PREFLIGHT ONSET TIME - SUPINE

	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2
30/CW	1.90	2.70	3.80	3.10	3.80	0.50	2.20	3.00	1.20	1.50
45/CW	1.70	4.40	3.00	1.80	1.20	3.00	1.60	1.10	0.90	1.40
60/CW	2.00	2.50	2.30	**	1.20	1.80	1.40	1.80	1.80	1.80
30/CCW	2.30	6.90	0.70	2.40	2.20	2.90	2.30	1.80	1.00	1.40
45/CCW	2.10	3.50	2.40	1.50	1.70	0.50	2.30	4.10	1.30	1.20
60/CCW	2.50	**	2.20	**	1.40	0.40	1.50	1.50	2.80	0.90

FLIGHT ONSET TIMES

	MD1	MD2		MD4		MD5	MD6	
	FREE	FREE	TACTILE	FREE	TACTILE	FREE	FREE	TACTILE
30/CW	1.98	1.83	1.39	1.78	1.15	1.55	1.34	1.36
45/CW	2.91	1.24	9.62	**	1.22	1.50	1.42	2.31
60/CW	1.20	1.82	1.71	**	4.27	1.82	1.19	3.44
30/CCW	1.71	1.77	2.36	**	1.92	1.18	1.50	1.01
45/CCW	2.20	1.00	1.51	1.29	1.65	2.12	3.66	1.51
60/CCW	1.51	1.40	1.55	1.21	2.77	2.00	2.39	1.53

**Data not available or inadequate for analysis

Subject	A	B	C	D
Average Preflight*				
Left	4.0±1.3	0.8±0.7	1.5±0.4	2.0±0.6
Right	5.0±2.1	1.5±0.6	1.5±0.8	1.5±0.7
Average	4.5±1.7	1.1±0.7	1.5±0.6	1.8±0.3
Average Postflight**				
Left	8.0±1.3	1.5±0.5	2.0±0.8	5.0±3.3
Right	3.5±1.3	2.5±1.1	1.8±0.5	3.3±3.4
Average	5.8±1.3	2.0±0.8	1.9±0.7	4.2±3.4

*Average of four tests taken at 122, 65, 44, and 10 days before flight.
**R+0, R+1 for subjects A and B, R+1 only for subjects C and D.

Table 4. Average and standard deviation of all preflight clockwise and counterclockwise performances on the rod and frame test compared to average of R+0, R+1 performances.

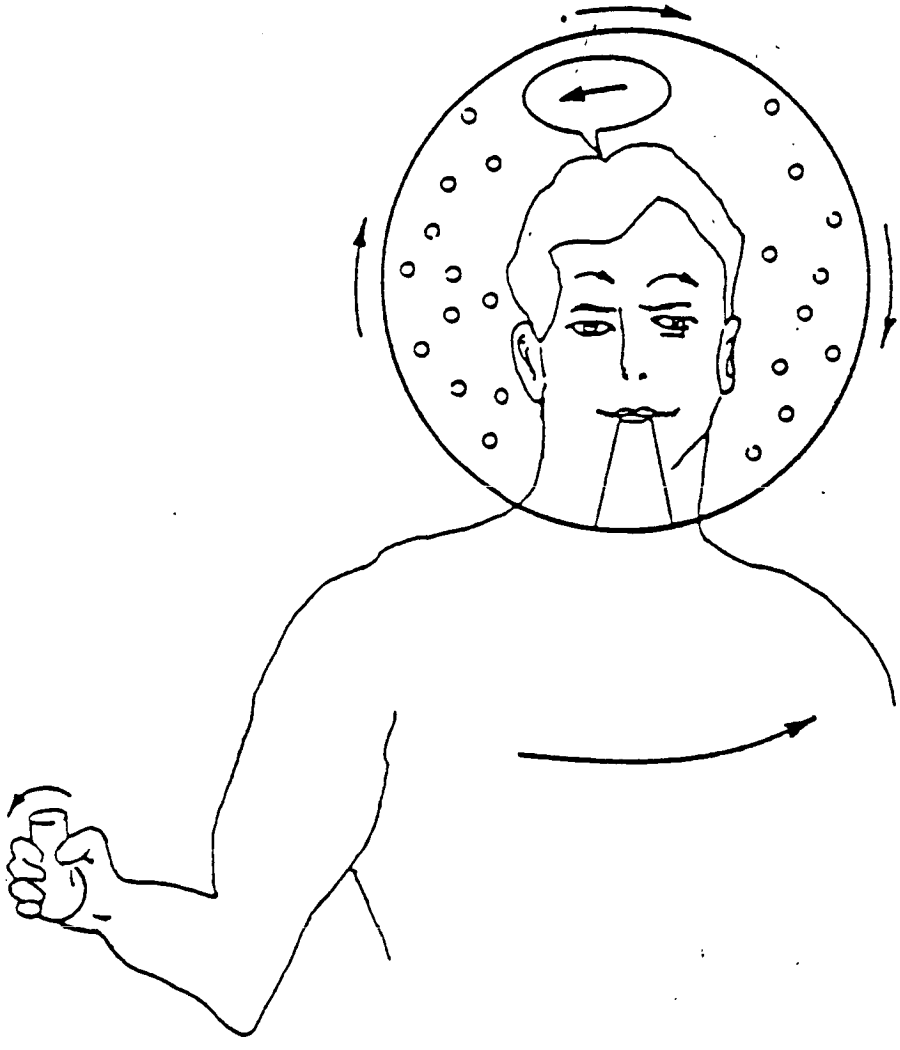
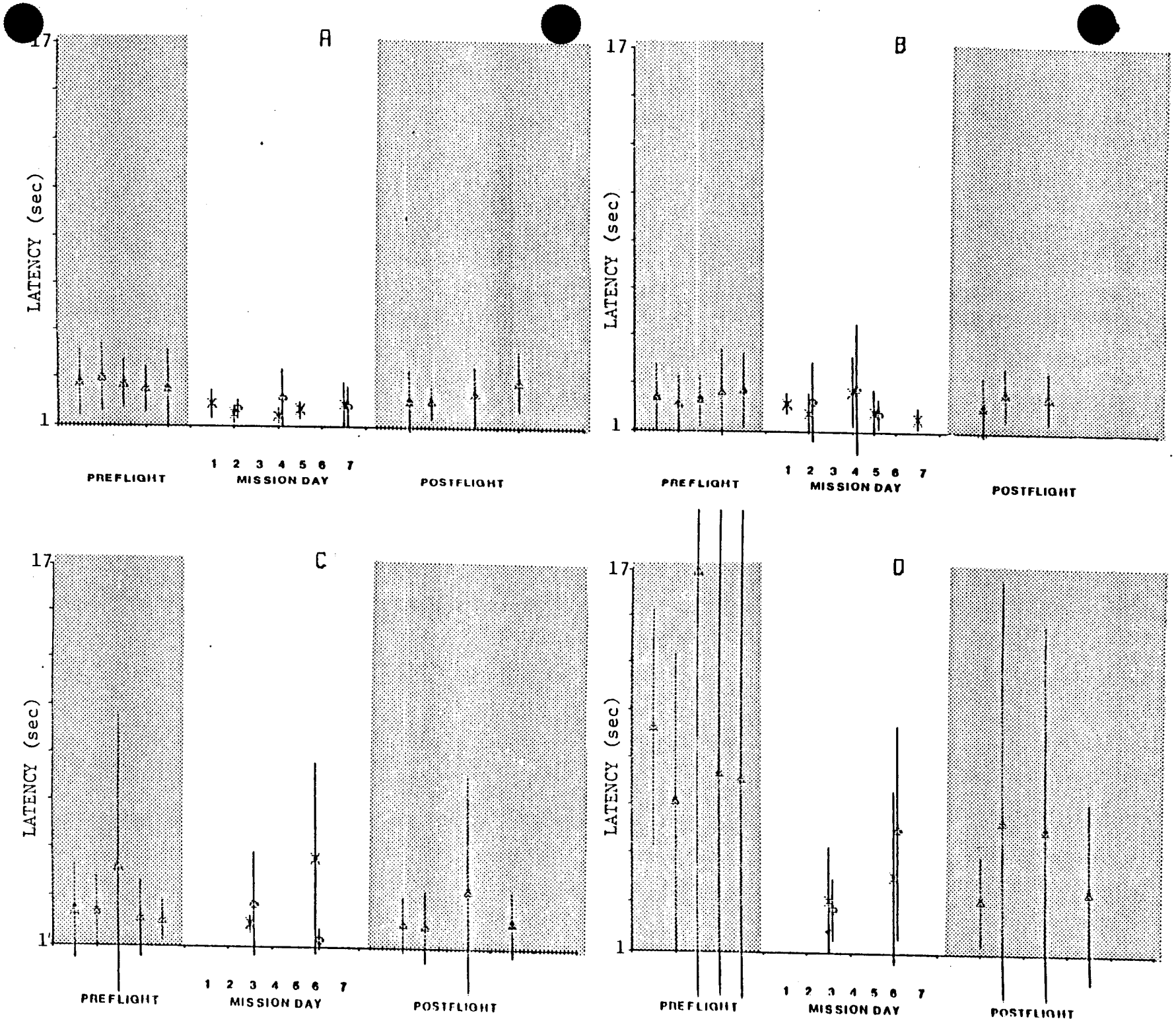


Fig. 1


A
B
C
D
17
1
LATENCY (sec)
PREFLIGHT
1 2 3 4 5 6 7
MISSION DAY
POSTFLIGHT

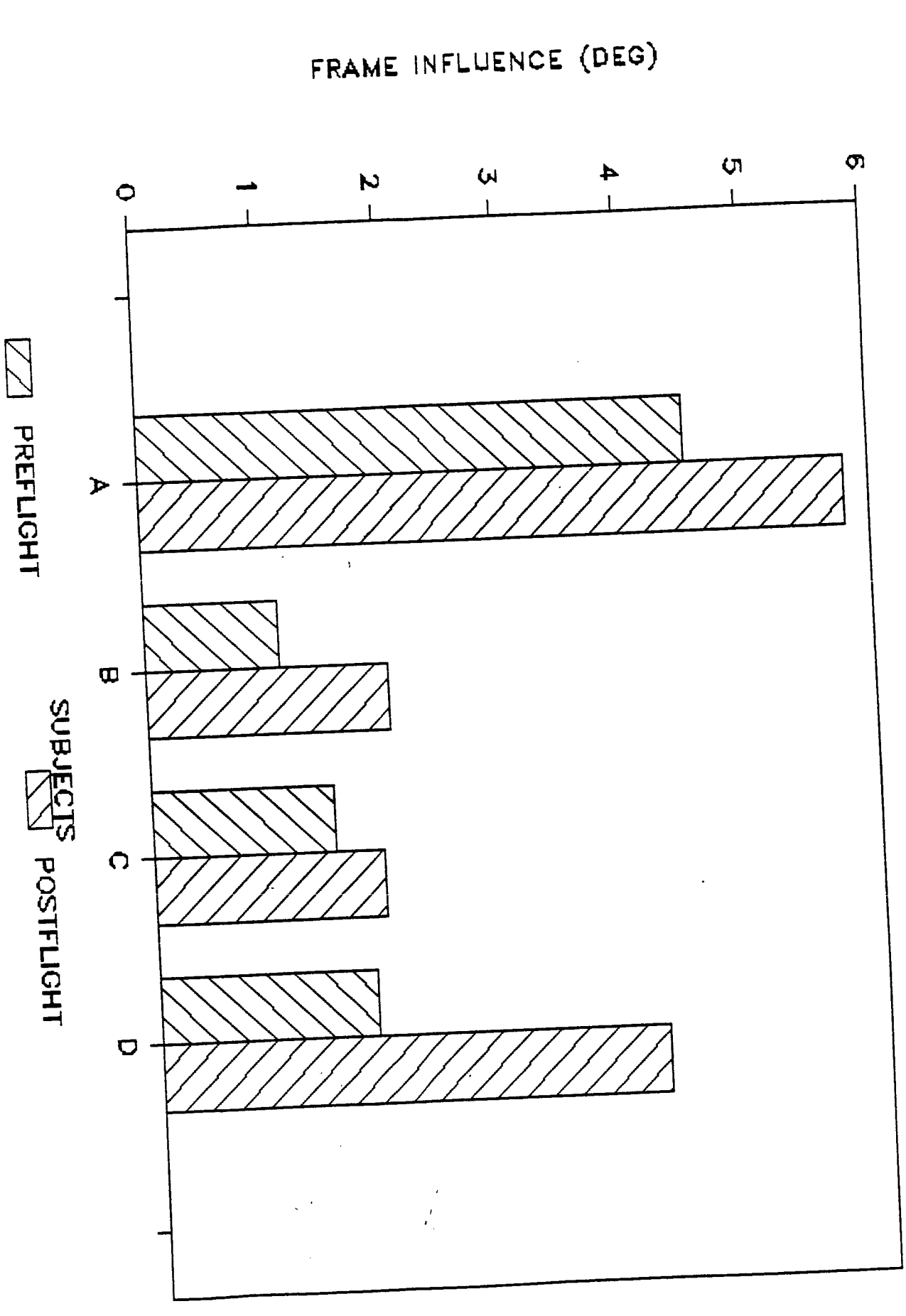

FRAME INFLUENCE (DEG)
0
1
2
3
4
5
6
A
B
C
D
SUBJECTS
PREFLIGHT
POSTFLIGHT

Fig. 3

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EFFECTS OF PROLONGED WEIGHTLESSNESS ON A HUMAN OTOLITH-SPINAL REFLEX

MIT/Canadian Vestibular Experiments on Spacelab-1: Part 3

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SUMMARY

Reflex responses that depend on human otolith organ sensitivity were measured before, during and after a 10 day space flight. Otolith-spinal reflexes were elicited by means of sudden, unexpected falls. In weightlessness, "falls" were achieved using elastic cords running from a torso harness to the floor. Electromyographic (EMG) activity was recorded from gastrocnemius-soleus. The EMG response occurring in the first 100-120 msec of a fall, considered to be predominantly otolith-spinal in origin, decreased in amplitude immediately upon entering weightlessness, and continued to decline throughout the flight, especially during the first two mission days. The response returned to normal before the first post-flight testing session. The results suggest that information coming from the otolith organs is gradually ignored by the nervous system during prolonged space flight, although the possibility that otolith-spinal reflexes are decreased independent of other otolith output pathways cannot be ruled out.

Key Words: Otoliths, otolith-spinal, falls, proprioception, muscle.

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INTRODUCTION

Within the vestibular labyrinth, the function of the otolith organs is to sense linear accelerations and gravity. In the free-fall or weightless condition of orbital space flight, the loss of the gravitational component must lead to familiar bodily movements producing abnormal neural signals. Faced with this, the nervous system must learn to reinterpret afferent information from the otolith organs and so make it useful again, or it must somehow ignore this potentially disruptive source of information, substituting other sensory inputs where possible. Some anti-gravity reflexes may not have any functional relevance in weightlessness and may be ignored in the adaptive process.

Since it is not possible to study the human otolith organs directly, it is necessary to take advantage of one or more of their 3 major output pathways. These pathways include projections to (i) higher centers, allowing conscious perception of linear motion and orientation, (ii) the extra-ocular muscles, responsible for nystagmoid or static (e.g. counter-rolling) eye movements, and (iii) the spinal cord, serving vestibulo-spinal reflexes. In the present experiment, the last of these has been chosen as a means of monitoring changes in otolith organ function. The stimulus used was produced by sudden, unexpected falls, a form of controlled and reproducible step input of linear acceleration. The response, which occurs in many flexor and extensor muscles throughout the body but is most conveniently recorded in gastrocnemius-soleus, takes the form of 2 bursts of electromyographic (EMG) activity, arbitrarily termed early and late. The latter is complex in nature, is responsible for controlling landing on the ground, and will not be considered here. The early burst, occurring from 50 to 150 msec after the onset of fall, is considered to be predominantly otolith-spinal in origin (Watt, 1976). Its time of onset is fixed relative to the moment of release and is independent of fall height. Its latency is too short and too invariant for a voluntary response (Melvill Jones and Watt, 1971a). The early burst can be abolished by labyrinthectomy in cats (Watt, 1976) and baboons (Lacour et al., 1978), and is absent in labyrinth-defective humans (Greenwood and Hopkins, 1976a). Plugging of the semicircular canals in cats has no effect on the response (Watt, 1976), confirming its origin in the otolith organs.

Previous studies have shown that the early burst can be a useful test of the otolith-spinal system under conditions of altered gravity. It is proportional

to the size of the acceleration stimulus (Greenwood and Hopkins, 1976b); it does not habituate with repeated testing, at least following the first drop (Wicke and Oman, 1982); it is reduced by rotating the gravity vector 90° relative to the body (Backman and Watt, 1979) or by eliminating that vector for short periods of time during parabolic aircraft flight (Watt and Backman, 1980). At least part of the response steadily increases in size during prolonged exposure to the supine position (Watt and Zucker, 1980). The present experiment used this method as a means of assessing changes in the otolith-spinal system during and after the prolonged weightlessness of space flight. In a broad sense, these changes suggest how the otolith-spinal system adapts to a new sensori-motor environment, and how it readapts to the presence of gravity after landing. Since it is not possible to fall in weightlessness, a physically similar step change in linear acceleration was produced by accelerating subjects footward with stretched elastic cords.

METHODS

(Figure 1 near here)

(Begin small print here)

The Acceleration Stimulus

Figure 1 illustrates the way in which each fall was carried out on the ground. In A, the subject has reached over his head and grasped the horizontal bar of an inverted T-shaped handle. The height was adjusted so he could just wrap his hands around the bar while keeping his heels on the ground. In B, keeping his head upright, his eyes looking straight ahead and his arms straight, the subject has lifted his feet 10-15 cm off the floor. By forcing the subject to flex his hips and knees in this way, the chances of skeletal injury are minimized should the handle release inadvertently. In C, the handle has been released, the subject has fallen to the floor and has landed successfully. The fall was preceded by a cue of "READY" spoken by the experimenter 1 to 4 seconds before release. The fall was therefore anticipated, but the exact time of onset was unknown to the subject.

Each test session included 45 falls, with a stimulus of Δ0.2 g for the first 15, Δ0.5 g for the next 15 and Δ1.0 g for the final 15. To achieve stimuli of less than Δ1.0 g (a transition to free fall), the subject wore a parachute harness which was attached by cables over pulleys to counterweights.

The experiment in Spacelab utilized the torso harness and elastic (bungee) cords illustrated in Fig. 1D. A total of 9 cords, in 3 sets of 3, ran from the harness to attachment points on or near the floor. When properly adjusted, they provided a floorwards force equal to the subject's weight as he hung by his arms from the handle. By removing one bungee from each set the acceleration stimulus was reduced to Δ0.67 g, and by removing another from each set it was reduced further to Δ0.33 g. Although the accelerating force necessarily fell off as the bungees shortened during each fall, all data were collected in the first 150 msec after release. Given a mean latency of approximately 75 msec for the EMG response to sudden falls (Melvill Jones and Watt, 1971), any changes in acceleration occurring more than 75 msec into the fall should not have had any effect on the present results. In the initial 75 msec, the subject fell less than 2.75 cm when using all 9 bungees, and the accelerating force fell by approximately 8%. For the first part of the early burst (sub-component 1, to be described later), the fall-off of force was much less than 8%. It was also less when using fewer than 9 bungees.

Data Recording

The EMG response to sudden falls was recorded from 2 surface electrodes (Hewlett Packard type 14445A, pre-gelled, disposable) located 6-7 cm apart over the lower ends of the lateral and medial heads of gastrocnemius of the left leg. A ground electrode was placed on the midline over soleus 5-10 cm below the others. Electrodes were always applied in the same locations, using tattoo marks as a reference. To minimize the possibility of motion artifacts, the skin was always de-greased with alcohol where the electrodes were to be located, and a small scratch was made with a sterile needle to reduce skin electrical resistance. EMG signals were amplified differentially and band-pass filtered between 50 and 350 Hz, using a Denver Research Institute special purpose amplifier.

During pre and post-flight testing sessions, the onset of fall was detected by a microswitch located in the releasing device. Contact with the ground was determined using a series of ribbon switches located under a section of carpet upon which the subject landed. Release, contact and EMG signals were recorded on analog tape, which was played back later for detailed computerized

analysis. All test sessions were also recorded using a television camera and video cassette recorder.

During in-flight testing, head longitudinal (Z-axis) acceleration was recorded using an accelerometer strapped to the subject's head and an electronics package worn at his waist (Fig. 1D). This signal was used to confirm both the times of onset of fall and of landing, and the magnitude of the acceleration stimulus. The primary method of determining the onset of fall was to monitor the release command sent to the handle solenoid by the computer. Contact with the floor was detected by means of a ribbon switch shaped like the sole of a shoe and attached under the subject's left foot. EMG, acceleration, release and contact signals, and TV pictures of the experimental session were all converted into a digital format, and relayed to the ground. Further data reduction was carried out after the flight.

Data Analysis

The filtered EMG signal was sampled at 1400/sec for the pre and post-flight data, and 1333/sec for the in-flight results, the latter rate being set by telemetry constraints. For each set of 15 falls at a particular acceleration, EMG activity was synchronized with respect to the onset of fall, rectified and averaged across trials. To compare between these average curves, the mean level of EMG activity was calculated within certain time gates following release. Delays between the release signal and actual release were taken into account. Falls were only accepted as part of the average if the subject's feet had not contacted the ground within 150 msec of onset of fall, and if no EMG activity was present prior to release.
(End small print here)

RESULTS

(Figure 2 near here)

The Response to Sudden Falls

All 4 Spacelab-1 payload crewmembers were tested repeatedly before and after flight, but only 2 subjects (A and B) were able to participate both while in space and on landing day. Subject A was tested on mission days 0, 1 and 6, and

Subject B on mission days 0, 1, 6 and 7. Figure 2 illustrates EMG responses recorded from Subject B. Each record is 200 msec in duration, with 25 msec shown before the moment of release and 175 msec after. The 3 examples of raw EMG on the left were recorded during the first pre-flight, in-flight and post-flight test sessions respectively. Each is the response to the first of 15 consecutive ∆1.0 g stimuli. The 3 average curves on the right include those falls plus the 14 others that followed immediately in each case.

Lacour et al. (1978) have demonstrated in the baboon that the so-called early burst actually consists of 2 sub-components. The two can usually be distinguished quite easily in average responses by a sharp increase of slope of the curve (the second sub-component is often much larger than the first), or by the presence of 2 distinct humps with a valley in between. The latency at which one divides the early burst into first and second sub-components varies somewhat between subjects, but is quite constant from test session to test session for any given subject. Of course, it is a quite arbitrary division, and overlapping of the 2 sub-components should be expected. Taking all of his average curves into account, the dividing line for subject B was set at 120 msec after onset of fall. Therefore, sub-component 1 would extend from 50 to 120 msec after release, and sub-component 2 from 120 to 150 msec.

It has also been shown that the 2 sub-components can change independently during prolonged exposure of subjects to the supine position (L. Tomi, personal communication). That is confirmed by subject B's results, as it is evident that while sub-component 1 decreased in weightlessness, sub-component 2 increased quite dramatically. Furthermore, it has been demonstrated that whereas sub-component 1 is not susceptible to voluntary control, sub-component 2 can be influenced by mental set (L. Tomi, personal communication). A subject who is experiencing discomfort or who chooses not to respond to a fall can largely abolish sub-component 2, but sub-component 1 will remain. In many ways, sub-component 1 and sub-component 2 seem comparable to the monosynaptic reflex and functional stretch reflex respectively evoked by sudden, maintained muscle stretch (Melvill Jones and Watt, 1971b). If the comparison holds, sub-component 1 is the result of a direct otolith-spinal reflex, but sub-component 2 is more of a triggered motor response which may involve the cerebellum or other higher structures.

Activity beginning more than 150 msec after the onset of fall probably is at

least partly voluntary in origin. In the examples shown in Fig. 2, it almost appears to be a third sub-component of the early response. However, if the subject had been raising his feet higher, contact with the ground would have occurred later, and this activity which anticipates landing would also have been delayed (Greenwood and Hopkins, 1976a and b; Watt, 1976).

(Figure 3 near here)

Two Subjects Tested Pre, In and Post-Flight

Each average curve of the type illustrated in Fig. 2 was divided into 2 parts (sub-component 1 and sub-component 2) as defined previously, and the mean EMG amplitude was determined for each part. These data were then normalized with respect to the average response of that subject obtained with a Δ1.0 g test stimulus at the final pre-flight test session, and plotted as a function of time before, during and after flight. The resulting graphs for subjects A and B are shown in Fig. 3, which includes separate curves for each stimulus strength, and each sub-component of the early burst.

Sub-component 1 (upper graphs) behaved quite similarly in both subjects. In nearly every case, the size of the response increased with the strength of the acceleration stimulus. There was no apparent change of the response post-flight relative to pre-flight. Sub-component 1 decreased significantly immediately upon reaching orbit, and declined further during the flight, with most of the latter reduction occurring between mission days 0 and 1. After mission day 0, stimuli of Δ0.33 g and Δ0.67 g were close to or below threshold for eliciting a response to sudden falls. Note that the Δ0.33 g and Δ0.67 g stimuli used on-orbit were greater than the Δ0.2 g and Δ0.5 g stimuli used on the ground. This makes the initial reduction of the response even more striking.

Sub-component 2 (lower graphs) was quite different, however. Except for in-flight, the response did not usually increase with the acceleration stimulus. Post-flight, a stimulus of Δ0.2 g (dotted line) tended to elicit a smaller response than the same stimulus pre-flight. In-flight, each subject seemed to adopt a different strategy. Sub-component 2 in subject A decreased upon entering weightlessness, and then changed little throughout the flight. In subject B however, sub-component 2 resulting from a Δ1.0 g stimulus

increased dramatically, whereas those resulting from ±0.33 g and ±0.67 g stimuli were decreased on mission day 0. All 3 continued to decline throughout the flight, however, and a stimulus of ±0.33 g was sub-threshold on mission days 6 and 7.

(Figure 4 near here)

Four Subjects Tested Pre and Post-flight

Figure 4 combines the results from subjects A and B (2 upper graphs of Fig. 3) with results obtained from subjects C and D. Again, mean EMG amplitude has been normalized with respect to the response to a ±1.0 g stimulus at the last pre-flight test session, and plotted as a function of time before, during and after flight. Each value is the average across subjects, ± 1 standard error of the mean where results are available for 4 subjects. Note that in-flight and day 0 post-flight data points derive from subjects A and B only, and the day 7 in-flight values were obtained from subject B alone. Because of the extreme variability of sub-component 2 between subjects, only sub-component 1 results are included here.

No significant trends were noted in the data pre or post-flight, nor was there a significant difference post-flight compared to pre-flight. This indicates that re-adaptation of the otolith-spinal system under study is a very rapid process, occurring much quicker than the original adaptation to weightlessness.

The average in-flight results, which were obtained from subjects A and B only, again present the evidence that sub-component 1 decreases immediately upon entering weightlessness, and then continues to decline, especially early in the flight. Stimuli of ±0.67 g or ±0.33 g are close to or below threshold after the first day on-orbit.

Subjective Findings

As expected, the sensation of falling in-flight was somewhat different than on the ground. While the initial acceleration felt reasonably familiar, the landing was more gentle due to decreasing tension in the bungees. Subject B commented that falls early and late in the flight felt the same to him.

Immediately post-flight, although the fall onsets felt more or less normal, the landings were not as comfortable. The subjects indicated that they felt heavier than normal, that the landings seemed faster and harder than pre-flight, and that their legs were bending more than before. They said that drop-testing was tiring, more work than pre-flight, and left them a bit short of breath. These effects were still present but greatly reduced the following day, and were nearly gone within 48 hours of landing.

All 4 subjects were quite unsteady on landing from falls for the first 48 hours after flight. Subject A, when tested 4.0 hours after landing, was unable to maintain his balance at all, falling over backwards into the arms of an experimenter after each drop. He commented that his legs, which he could not see, were always further forward than he thought prior to the falls, by perhaps 1 or 2 cm. This was confirmed by an observer, and may have been present late in-flight as well.

Subject B, when tested 5.5 hours after landing, also described an unusual illusory sensation while rhythmically hopping up and down on both feet. He said "the floor was coming up to meet me", and that "the floor was there before I was ready for it on the way down". This illusion, which was particularly pronounced in the first 10 or 15 minutes after landing but essentially gone within 24 hours, felt not unlike hopping on a trampoline. It was also accompanied by some apparent movement of the visual world during the hopping. A similar sensation was experienced during deep knee bends performed post-flight (Kenyon and Young, 1986).

DISCUSSION

In the analysis of these experiments, the early burst of EMG activity caused by sudden falls has been divided into 2 sub-components, and it has been assumed that sub-component 1 is mediated by shorter, more direct otolith-spinal pathways than sub-component 2. The gain of this more direct otolith-spinal system has been shown to decrease immediately upon entering weightlessness, to decline further during prolonged exposure to zero g, and to return to normal immediately upon landing. Based on the present evidence, it is not possible to determine the exact location of the underlying changes in nervous system function. The H-reflex study conducted on subject A by Reschke (1984) suggests

that the reduced responses were not the result of decreased spinal cord excitability, however.

The immediate decrease in sub-component 1 upon entering weightlessness was expected, as it had been demonstrated earlier during parabolic aircraft flight (Watt and Backman, 1980). Since the threshold of perception of Z-axis linear oscillation is also raised in weightlessness (von Baumgarten et al., 1984), it would seem that changes in the peripheral organ or in neuronal pathways common to both conscious perception and otolith-spinal reflexes are responsible. The response characteristics of otolith organ primary afferents are known to be non-linear (Fernandez and Goldberg, 1976), and it may be that the absence of the normal 1 g bias has forced these afferents into less sensitive parts of their operating range. As a result, the same step input stimulus would produce a smaller response.

The progressive decline of sub-component 1 during the flight, especially between mission days 0 and 1, occurred even though the acceleration stimulus remained the same. This was not simply the result of habituation to the stimulus, since none occurred during the intensive post-flight testing period. The decline was also noted by Reschke (1984) as a lessening of H-reflex potentiation during falls in weightlessness. This decrease in gain of the otolith-spinal system tends to suggest that during space flight, the nervous system reacts to confusing otolith afferent information by gradually learning to ignore those organs. It must be remembered, however, that the present study cannot discriminate between adaptation occurring in the peripheral organ, in the brain stem, or in the spinal cord. It is quite conceivable that the decreased sensitivity is selective to the otolith-spinal system, reflecting the new irrelevance of this postural control pathway in weightlessness. There is some evidence suggesting that the spinal cord can be receiving valid otolith-mediated information on body acceleration at a time when areas responsible for conscious perception are not (Watt, 1977). Possibly the reverse could be true here, with otolith-spinal pathways suppressed while higher centers remain available to reinterpret the novel pattern of otolith afferent activity.

Readpatation to the normal gravity environment occurred more rapidly than the adaptation to weightlessness. In fact, it is not clear if there actually was a readaptive time course, or if the change was essentially instantaneous.

This conflicts with the findings of Reschke (1984), who noted extremely large potentiations of the H-reflex up to a week post-flight. At this time, the reason for this difference in results remains unknown.

Late in-flight, and especially on the first day after landing, there were hints that proprioceptive function might not be normal in several of the subjects. Further complicating the issue was muscle wasting, which was quite striking in several subjects. These observations support the view that the postural instability seen post-flight may be more the result of faulty proprioception and motor system problems, and less the result of incorrect otolith-spinal information. This is consistent with the posture platform studies of the Spacelab-1 crewmembers reported by Young et al. (1984) and Kenyon and Young (1986), in which the early vestibular component of the response to postural perturbations was not altered post-flight.

Finally, it was somewhat surprising when subject B commented that falls felt the same both early and late in the flight, despite the significantly smaller EMG responses (both sub-components) on mission days 6 and 7. While this may only reflect the fact that vestibular projections to the spinal cord and higher centers can be modified independent of one another, it could also indicate that otolith organ stimulation contributes little to the conscious sensation of linear motion and "falling". This would be compatible with the fact that free-fall experienced in space or during parabolic aircraft flight elicits no subjective sensation of falling whatsoever, despite the fact that these situations are closely comparable in a physical sense (excluding air resistance) to the short-duration falls used for test purposes in this experiment. The latter produced a strong feeling of falling which was not changed by closing the eyes or by wearing a flight suit (which minimized tactile stimulation by air flow), and which was also not changed following 10 days in space.

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LEGENDS FOR FIGURES

Fig. 1. Pre and post-flight, sudden unexpected falls were obtained as shown in A-C. The subject grasped a handle (A), raised his feet (B) and when the handle was released, he dropped and caught himself with his legs (C). In-flight (D), elastic cords running from a torso harness to the floor substituted for gravity, but the test sequence was otherwise the same. Subjects were always instructed to return to a full standing position as quickly as possible following each fall, regardless of when they were being tested.

Fig. 2. The 3 records on the left are examples of filtered raw EMG activity recorded from subject B during sudden Δ1.0 g falls before, during and after the SL-1 mission. Each is 200 msec in duration, with 25 msec before and 175 msec after release. The 3 curves on the right are examples of rectified and averaged EMG activity, obtained by combining the responses on the left with the 14 others that followed immediately in each of the cases. The vertical dashed lines indicate the limits of sub-components 1 and 2 of the early burst of EMG, with potentially voluntary activity following.

Fig. 3. Mean EMG amplitude (normalized with respect to the last pre-flight test with a Δ1.0 g test stimulus) plotted as a function of time before, during and after the flight. Separate curves have been drawn for each subject, each sub-component of the early burst, and each strength of stimulus. Pre and post-flight stimuli: solid line Δ1.0 g, dashed line Δ0.5 g, dotted line Δ0.2 g. In-flight stimuli: solid line Δ1.0 g, dashed line Δ0.67 g, dotted line Δ0.33 g. Stimulus strengths are also indicated in the lower right graph.

Fig. 4. Mean amplitude of EMG sub-component 1 averaged across all 4 subjects and plotted as a function of time before, during and after flight. All data have been normalized with respect to the last pre-flight test with a Δ1.0 g test stimulus (star), and are shown $\pm$ 1 S.E. of mean where results are available for all 4 subjects. Acceleration stimuli are indicated beside each curve.

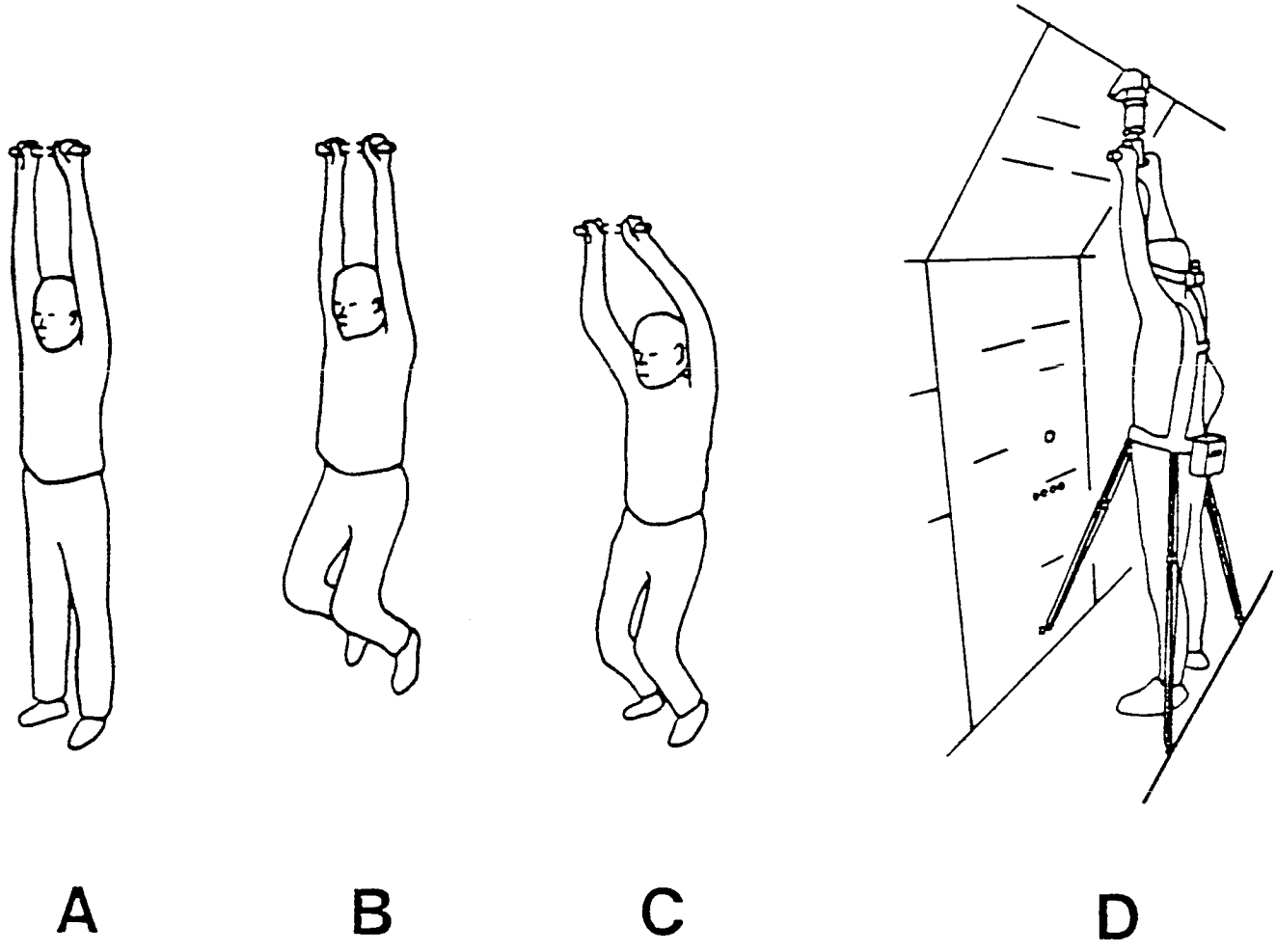

Figure 1

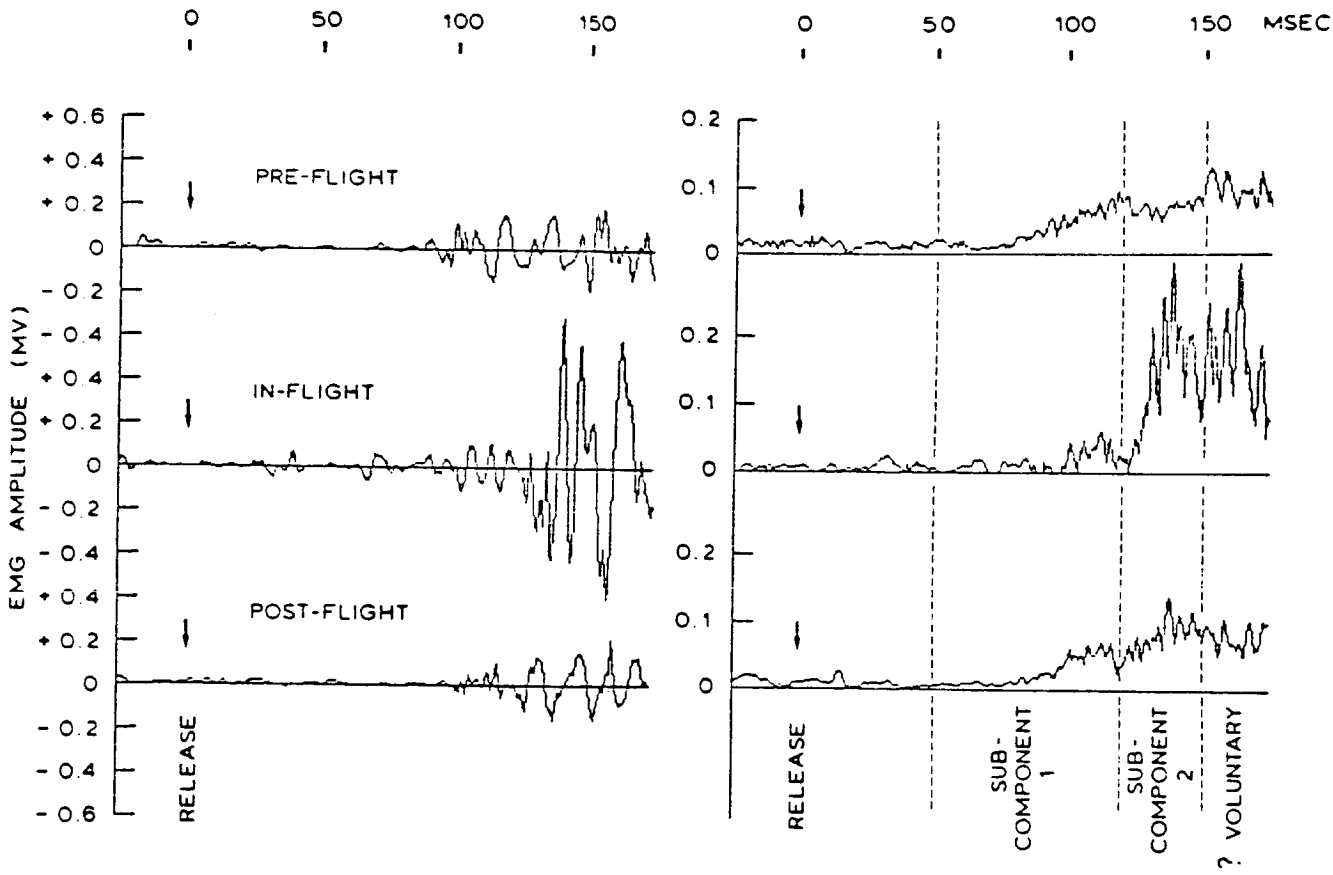
0
50
100
150
MSEC
EMG AMPLITUDE (MV)
+0.6
+0.4
+0.2
0
-0.2
-0.4
PRE-FLIGHT
IN-FLIGHT
POST-FLIGHT
RELEASE
0.2
0.1
SUB-COMPONENT 1
SUB-COMPONENT 2
? VOLUNTARY

Figure 2

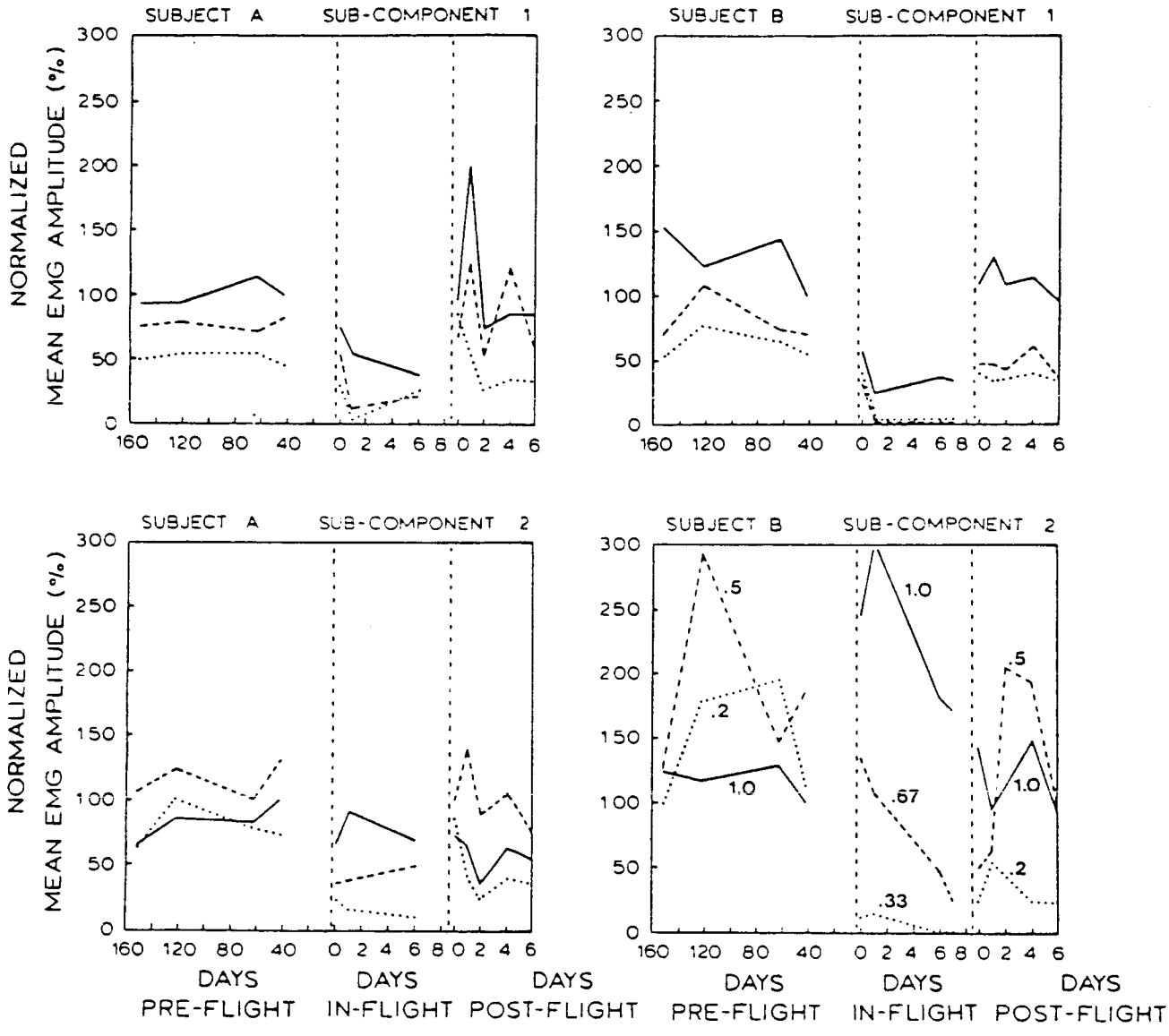
SUBJECT A
SUB-COMPONENT 1
SUBJECT B
SUB-COMPONENT 1
SUBJECT A
SUB-COMPONENT 2
SUBJECT B
SUB-COMPONENT 2
NORMALIZED MEAN EMG AMPLITUDE (%)
300
250
200
150
100
50
0
160 120 80 40 0 2 4 6 8 0 2 4 6
.5
1.0
.2
1.0
.67
.33
.5
1.0
.2
DAYS PRE-FLIGHT
DAYS IN-FLIGHT
DAYS POST-FLIGHT
DAYS PRE-FLIGHT
DAYS IN-FLIGHT
DAYS POST-FLIGHT

Figure 3

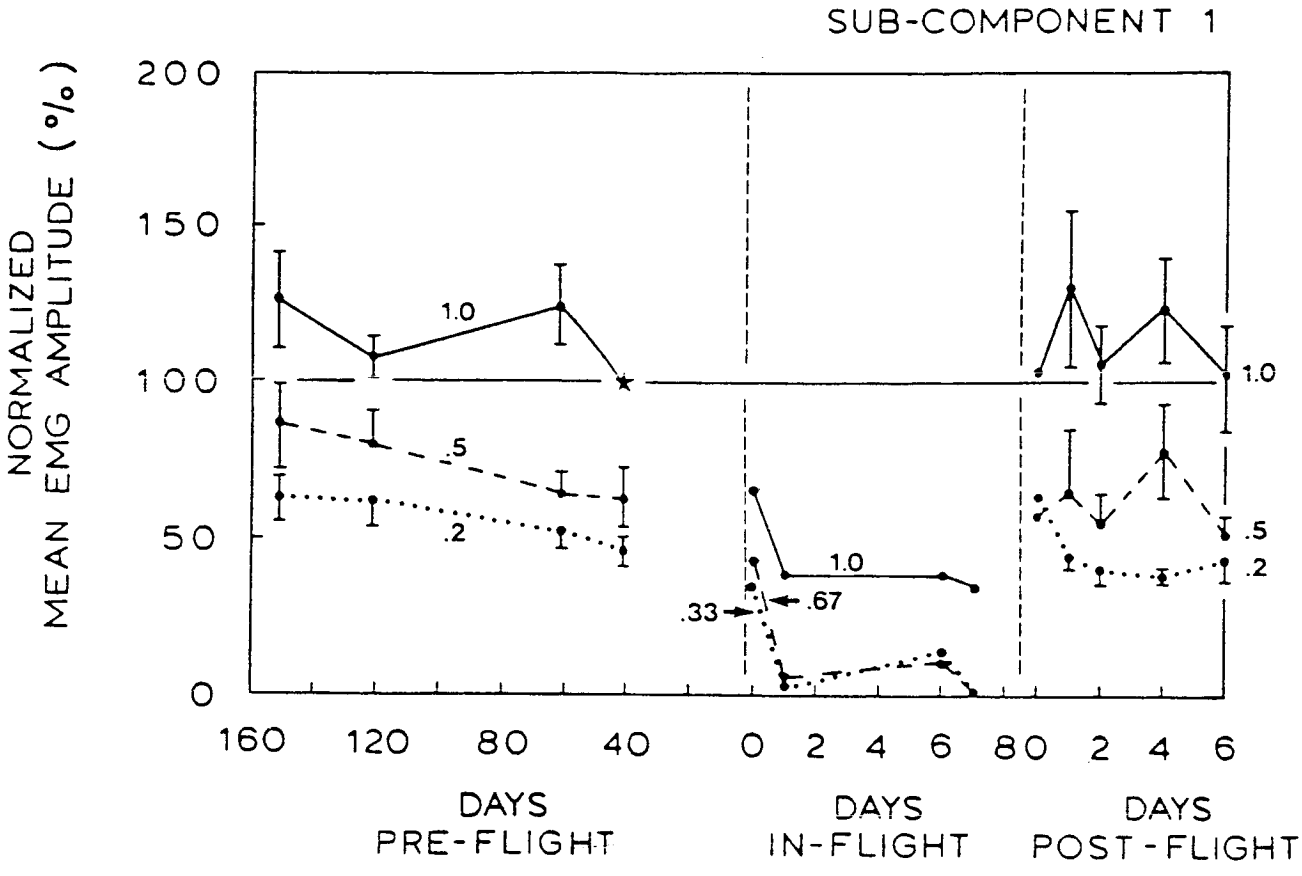
SUB-COMPONENT 1
NORMALIZED MEAN EMG AMPLITUDE (%)
200
150
100
50
0
1.0
.5
.2
.33
.67
160
120
80
40
0
2
4
6
80
2
4
6
DAYS PRE-FLIGHT
DAYS IN-FLIGHT
DAYS POST-FLIGHT

Figure 4

D4-52
47P.

SPACE MOTION SICKNESS: SYMPTOMS, STIMULI, AND PREDICTABILITY
MIT/Canadian Vestibular Experiments on Spacelab-1: Part 4

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SUMMARY: Space sickness symptoms were observed by 4 specially trained observers on Spacelab-1. Three reported persistent symptoms, and vomited repeatedly during the first and/or second day of flight. Head movements on all axes were provocative, particularly in pitch and roll. Head acceleration data recorded from 2 symptomatic crewmen showed that after several hours of physical activity in orbit, symptoms appeared. Thereafter both crewmen were compelled to limit head movements. Firm body contact with motionless surfaces helped alleviate symptoms. When crewmembers floated into unfamiliar body orientations in the cabin, inherent ambiguities in static visual orientation cues sometimes produced spatial reorientation episodes, which were also provocative. Symptoms largely resembled those of other forms of prolonged motion sickness, superimposed upon other symptoms attributable to fluid shift. All 4 eventually used anti-motion sickness drugs. When they did, vomiting frequency was reduced. By the 4th day, symptoms subsided, and head accelerations again increased in magnitude and variability. Sickness intensity in orbit was not predicted by statistically concordant results of 6 acute preflight susceptibility tests. However, results from a longer duration preflight prism goggles test showed an apparent correlation. All subjects were asymptomatic making head movements in parabolic flight 4 days after the mission, but not 1 year later. Overall, results support the view that space sickness is a motion sickness.

Keywords: space motion sickness; spatial orientation; vision; head movements; vomiting

INTRODUCTION:

Since the US Space Shuttle became operational in 1981, approximately half of the crew members have experienced symptoms during their first 3-5 days in weightlessness which qualitatively resemble those of motion sickness (Homick, et al, 1984). The malady is not a new phenomenon. It has been consistently reported by Soviet Cosmonauts (Matsnev, et al, 1983), beginning with the second manned orbital flight of Titov in 1961. Symptoms were not experienced by US Astronauts in Mercury and Gemini spacecraft. However, the disorder was reported by Apollo crews (Homick and Miller, 1975), and by 5 of 9 Skylab astronauts (Graybiel, et al, 1977). The occurrence of a motion sickness in weightlessness was fully predicted (Simons, 1955; Gerathewol, 1956; Lansberg, 1960) based on experience in early parabolic flights, and on the "sensory conflict" theory for motion sickness (see below). Because of this prediction, the reported similarity of symptoms and signs, and the absence of strong contrary evidence, it has been parsimonious (Benson, 1977) to assume that "space sickness" is a form of "motion sickness", and to refer to the disorder as "space motion sickness" (SMS). (The term "space adaptation syndrome" (SAS) has also been applied, although this term has recently been more broadly used to encompass all the acute physiological changes associated with weightlessness.) Nevertheless, for reasons reviewed below, the etiology of space sickness has remained controversial. In this paper, we present results from a head movement and symptom monitoring experiment and pre/postflight motion sickness susceptibility tests which were designed to systematically collect additional detailed information on the symptomatology, etiology, prediction, and prevention of the disorder. On this mission, we placed particular emphasis on resolving the issue: is space sickness really a motion sickness ? Preliminary reports containing some additional details are available in Oman, et al, 1984, and

Money, et al, 1984.

The controversy concerning the etiology of space sickness has arisen in part because the physiology of motion sickness itself is so poorly understood, despite significant research (reviewed by Tyler and Bard, 1949; Chinn and Smith, 1955; Money, 1970; Reason and Brand, 1975; and Graybiel, 1975): Individuals who lack vestibular function appear immune. Many brain stem and cerebellar "vestibular" neurons subserving oculomotor and postural control are now known to respond to a variety of spatial orientation sensory cues. A brain stem "vomiting center" (VC) and "chemoreceptive trigger zone" (CTZ) were identified in canine studies of motion sickness and vomiting. It was generally assumed that signals originating somewhere in the central vestibular system somehow traverse to the CTZ and thence to the VC and also to other centers which mediate other autonomic symptoms. However, the central vestibular structures and the emetic and autonomic linkages have not been physiologically identified. Recent experiments have questioned the localizability of the vomiting center and the role of cerebellar structures previously implicated in motion sickness (Miller and Wilson, 1983a,b).

The cardinal symptoms and signs (henceforth called "symptoms" for brevity) of motion sickness are stomach discomfort, nausea and vomiting. Other symptoms include pallor, cold sweating, salivation, respiration increase, belching, flatulence, decreased gastric tonus, stress hormone release, fatigue, and drowsiness, indicating that other areas in the brainstem reticular core, hypothalamus, pituitary, and adrenal cortex responsible for autonomic regulation are coactivated during sickness. (Money, 1970; Reason and Brand, 1975; Eversmann, et al, 1978) Motion sickness symptom intensity modulates with

stimulus strength, rate of onset, and duration. Typically there is a significant delay in the first appearance of symptoms (suggestive of an initial sub-threshold "cumulation" of the stimulus), a subsequent perseveration of symptoms and sensitivity to further stimulation after the initial stimulus is removed (Graybiel, 1975). Although an individual's threshold for sickness may vary significantly from day to day, once symptoms start to occur, they generally appear in a consistent pattern for a given individual in a given test. The characteristic symptoms of prolonged motion sickness differ in certain respects (discussed later) from those associated with acute laboratory motion sickness.

Although physiological understanding is thus far from complete, behavioral evidence has offered important clues, and has led to the development of "sensory conflict" hypotheses to explain the disorder (e.g. Claremont, 1931, Steele, 1963; Melvill Jones, 1974; Guedry, 1978; Reason, 1978; Oman, 1982a,b).Motion sickness consistently occurs during passive exposure to real motion (as in "seasickness", "carsickness", or "airsickness") or to apparent motion ("Cinerama sickness"; "flight simulator sickness"). It also is seen when the "rules" defining the normal relationship between body movement and the resulting sensory neural inflow to the brain are systematically changed (e.g. "spectacle sickness"; "Coriolis sickness"), circumstances termed "sensory rearrangement" (Held, 1961). The putative internal "sensory conflict" stimulus is thought to be a neural or humoral signal originating in centers responsible for processing body movement control and spatial orientation information. As movements are commanded, the CNS is assumed to continuously predict the corresponding sensory inputs which would normally be expected, based on an internal neural model for body dynamics and sense organ characteristics. "Sensory conflict" signals would result from a continuing comparison of actual sensory signals and anticipated

ones (Reason, 1978), and extract the unexpected component of sensory inputs. Thus, brief conflict signals would likely be frequently encountered in daily life, and be functionally useful in orientation perception and posture control. Increased conflict triggers motion sickness, but with most stimuli, only after prolonged stimulation. Adaptation could take place because of sensory/motor learning (via internal model correction), and/or by modification of the sensitivity and threshold of the emetic and autonomic centers in the brain (Oman, 1982a).

The conflict theory predicts motion sickness should occur in weightlessness, since the predictions of the internal neural models for the graviceptive modalities would be "incorrect" in weightlessness: In the absence of gravitational loading, each of the four otolithic membranes in the inner ear would be expected to assume new positions relative to the underlying sensory cells. The unfamiliar ensemble coded pattern of otolith afferent signals corresponds to that of a prolonged "fall", which is inconsistent with expected signals based on concurrent visual cues and motor commands. During head movements, the otolith afferent response to all head movements would be unfamiliar, until the new response pattern was learned by experience making head movements in weightlessness. Head movements in weightlessness should therefore be both a major cause and an ultimate cure for sickness. In fact, crew reports beginning with Titov's in 1961 have generally confirmed that head movements are a major stimulus for space sickness. (Homick and Miller, 1975; Graybiel, et al, 1977; Matsnev, et al, 1983). One might also predict that if visual cues to orientation were ambiguous in weightlessness, visual reorientation episodes could occur, and be provocative. There is now evidence that this is the case (Sect 2.2 below).

Although the "sensory conflict" hypothesis thus predicts space motion sickness, the theory derives from information processing considerations, rather than known physiological mechanisms. It posits neural processing strategies which are as yet largely unverified physiologically. It has as yet not been possible to successfully predict who will be most susceptible or adaptable under a given circumstance. Nonetheless, if space sickness is a motion sickness, one might hope that space sickness incidence or intensity could be predicted with preflight tests. However, as reviewed later, attempts to do this have not been successful. Although many of the symptoms of space sickness do resemble those of motion sickness, this similarity - taken alone - hardly proves that the causal mechanisms are necessarily the same. Because of these difficulties, alternative theories invoking possible physiological effects of fluid shift were suggested. The removal of the gravitational load on the cardiovascular system results in a shift of blood and interstitial fluid from the legs to the upper half of the body, and produces a variety of symptoms, including facial plethora, edema and nasal stuffiness, seen in virtually all crewmen. It has been speculated that fluid shift might induce nausea and vomiting through a direct effect on the CNS due to increased cerebrospinal fluid pressure or a change in its chemical constituency. Alternatively, such changes could produce inner ear pathology, leading to vertigo and motion sickness. However, supporting experimental evidence (reviewed by Talbot, 1983; Parker, et al, 1983) for these notions has been scant.

Drugs which have been employed against space sickness have usually been those known effective against motion sickness on earth. However, their efficacy has proven difficult to evaluate under operational conditions (Homick, et al, 1984). For example, 3 of 5 Skylab astronauts who took drugs on the first day of flight

a decade earlier. We trained them to observe the time course of symptoms and signs of space sickness and fluid shift, the relationship of these to head movements, and the effect of visual, tactile, and proprioceptive cues on spatial orientation and sickness intensity.

In order to document the relationship between head movements and symptom intensity, we asked Subjects B and C to wear a head Acceleration Recording System (ARU), shown in Figure 1: Three angular (Schaevitz ASM-300; 150 rad/sec 2 range) and 3 linear (Kulite GY-125-20; 20 g range) miniature accelerometers were mounted within a rectangular metal case so that the sensitive axes of the accelerometers were orthogonally oriented, and parallel to the sides of the case. This 0.3 kg package was held firmly in place over the occipital region of the head by a velcro adjustable cloth brow band so that it moved with the head during virtually all normal head movements. Because the headband was usually worn high on the forehead, the case was worn low, so that "yaw" and "Z" accelerometer axes were tilted some 20-30 degrees from the principal anatomical vertical (sagittal) axis of the head, and the "roll" and "X" axes were correspondingly pitched up above the head frontal axis. The accelerometers were connected via a flexible cable to a digital cassette tape recorder (NASA CDTR Model II, SRI International Inc.) which was worn on a waist belt along with a separate lithium battery power module. The recorder sampled each of the 6 accelerometer signals in the frequency range between 0 and 30 Hz at a 100 Hz. sampling rate with 10 bit resolution. Once per minute, time of day replaced one sample of data on all 6 recorder tracks. Data was stored on replaceable tape cassettes, which were normally changed every 8 hours. Subjects were asked to don the ARU as soon as possible after reaching orbit, and to wear it as much as possible during their waking hours, particularly during the first days of the mission.

For postflight analysis, data on 21 cassettes recorded during the mission was transferred to a (VAX 11/780) computer via a special playback unit, which simultaneously checked each data word for bit drop out errors introduced during the record/playback process. On average 10% of the data were in error, and on sections of individual tapes, this rate was occasionally much higher, with runs of consecutive errors several minutes in duration, due to various technical problems associated with the recorder, playback unit, and tape quality. The high error rate precluded the detailed time domain data analysis originally planned. Instead, we computed the acceleration amplitude distribution for each data channel over successive 15 minute time intervals, (as shown in Figure 2) discarding erroneous data words, and took the standard deviation of this distribution as an estimate of root mean square (RMS) head acceleration during this quarter hour period. For statistical analysis, we discarded the RMS acceleration estimate if the average error rate over the 15 minute interval exceeded 50%. A total of 69% of the total time period sampled from Subject B and 80% for Subject C remained.

Subjects used pocket voice recorders and a multi-item symptom checklist (Oman, et al, 1984) to record observations on symptoms as they were noticed and time permitted. The checklist included the individual elements of the Pensacola Diagnostic Criteria for Acute Motion Sickness (Graybiel, et al, 1968) plus additional items related to symptoms of prolonged motion sickness, fluid shift, and drug use. Subjects B and C were asked to make detailed checklist reports when possible as symptoms changed. To obtain frequent reports for correlation with head movement data, subjects were also asked to make frequent brief

reports, consisting of Mission Elapsed Time (MET) and a numerical magnitude estimate of "Overall Discomfort". Instructions were to "pick a sensation magnitude of overall discomfort in the middle of the "moderate" range, halfway to vomiting. Call this standard "10". Estimate the magnitude of overall subjective discomfort with respect to it. If no sensation, say 'absent'. If just noticeable, say 'threshold'." This method (Bock and Oman, 1982) was designed to produce a ratio scale (Stevens, 1957), and has also been useful in assessing the dynamics of the stimulus/response relationship in other forms of motion sickness (Oman, 1982a).

In addition to symptom monitoring, we asked Subjects B and C to make deliberately provocative head movements. The protocol consisted of a "Susceptibility Test" followed by a "Symptom Comparison Test", which explored the influence of eye closure and axis of head movement. These tests were scheduled for the end of the working day on Mission Days (MD) 0,3, and 8. If asymptomatic to start, the subject would strap into a seat and make 7 forehead to knee head movements (to a 1.5 sec/movement metronome cadence), then rest for 10 seconds while making a checklist symptom report, and then repeat until the first symptom occurred or 5 minutes elapsed. If symptoms were present at the start, this susceptibility Test would be skipped, and the subject performed only the "Symptom Comparison Test". In fact, the Comparison Test protocol required a slightly symptomatic subject, so that the head movement stimulus/response relationship would be immediately obvious. Subjects first made up to 7 forehead to knee movements eyes closed, and then repeated this eyes open, and ranked the two conditions in terms of provocativeness. After a pause for recovery, subjects were then to make 90 degree head movements (eyes open) for 20 second periods successively in pitch, yaw, and roll, with rests as necessary in between, and then to rank these movements also. The final decision whether or how far to proceed was left entirely in the hands of the subjects, who would be in the best position to know if continuing the test would significantly jeopardize the subject's physical capacity.

Training was accomplished during 1979-1983, and involved formal lectures, equipment operation, experience in parabolic flight with the role of visual, vestibular, and tactile cues on spatial orientation; experience with the subjective sensations of fluid shift (created by 30 minutes of 10 degree head down bedrest), and more than 12 hours of training in symptom evaluation. Training with a prolonged, head movement dependent stimulus ("Prism test") was accomplished in several 2-3 hour sessions in which the subjects wore left/right vision reversing goggles and walked about, as described in Oman, et al (1980) and Bock and Oman (1982), each performing the same types of physical tasks until activity became limited by developing symptoms. Susceptibility was measured as the time in minutes to sustained epigastric awareness or nausea, and adaptability subjectively ranked by an observer based on performance in obstacle avoidance and coordination tasks. Training with shorter duration (5 - 30 min)stimuli was conducted in conjunction with a series of preflight motion sickness tests, which included:

a) "PAM" Tests A (Feb 79) and B (Apr 83). Whole body pitch rotation about a horizontal axis with eyes open in the closed cabin of the DCIEM "Precision Angular Mover" at 20 RPM to a slight but unequivocal nausea endpoint ("PAM test"; Leger, et al, 1981) or 10 minutes. Susceptibility was computed as the maximum number of Pensacola Diagnostic points observed during and immediately after the test, divided by the test duration.

b) "KC-135" Test (Mar 83). Forehead to knee head movements made with eyes open while seated during the weightless phase of parabolic flight in the NASA KC-135. Seven head movements per parabola were made until a slight but unequivocal nausea endpoint or 20 parabolas was reached. Head movements were not permitted during the hypergravity portion of the parabolas. Susceptibility was based on total Pensacola Diagnostic points observed and the time to endpoint. This test was repeated postmission on the fourth day after landing (Dec 11 83) and again one year later (Dec 1984).

c) "VVI" Test (Feb 79). Angular acceleration about an earth vertical axis at 0.02 Hz., 155 deg/sec peak velocity with eyes open in a closed cabin while reading digits upon command from a matrix display. (Brief Visual/Vestibular Interaction Test; Moore, et al, 1977). Susceptibility was the total number of symptom points observed during this 5 minute test.

d) "CSSI" Test (Jun 83). Coriolis Sickness Susceptibility Test. Rotation about an earth vertical axis with 4 quadrant out of rotation plane head movements. Susceptibility was the total number of head movements required to reach a "Malaise III" Pensacola Diagnostic endpoint, weighted by an RPM dependent factor. (Miller and Graybiel, 1970)

e) "CSVT", a Coriolis Stair-Case Velocity Test (Jul 81). Rotation about an earth vertical axis with 4 quadrant head movements, beginning at 11 RPM. After every 40 head movements, RPM increases by 2. Susceptibility was total number of head movements required to reach a "Malaise III" endpoint. (Homick, et al, 1983)

Additional details on Tests a-c are available in Money, et al, (1984). Tests d) and e) above were conducted by the Operational Medicine Branch of NASA Johnson Space Center. Tests d) and e) served a second purpose as controls in a study to select a suitable anti-motion sickness drug for each crewmen based on efficacy and acceptability of side effects. Drugs chosen were 0.4 mg. scopolamine /2.5 mg dexedrine ("scop/dex") in capsules and 25 mg. promethazine /25 mg. ephedrine ("P/E"). In addition, 2 Subjects chose to evaluate the effects of 10 mg. metoclopramide (Reglan) on orbit.

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RESULTS AND DISCUSSION:

Our results and discussion on space sickness divide most easily into four separate topics: symptom pattern, adequate stimuli, drug effectiveness, and pre/postflight susceptibility test results. Each of these topics is considered successively in numbered sections below. In each section, results are presented first, followed by discussion.

1. Symptom Pattern: The 10 day Spacelab 1 mission was launched November 28, 1983. The crew work schedule required substantial early mission physical

activity to activate the Spacelab module and deploy experiments. As planned, Subjects A and D took scop/dex immediately upon reaching orbit. Subjects B and C did not employ drugs prophylactically, but eventually respectively resorted to Scop/Dex and P/E for treatment. Subjects A, B, and C experienced persistent symptoms (latency range 2.4 - 5.8 hr), although of different intensity and time course. These 3 vomited repeatedly during the first and/or second day, despite the use of scop/dex or P/E, as shown in Figures 3 and 4. Only Subject D was free of significant symptoms. The effectiveness of these phamacologic countermeasures is discussed later (Sect. 3.)

Subject B was able to provide detailed symptom reports, as well as frequent overall discomfort magnitude estimates. The time course of his overall discomfort scores and drug use are shown in Figures 5 and 6 for the first two days of the mission, when his discomfort was most intense. In these figures, the curves between individual data points were interpolated based on additional notes made at the time, and by Subject B himself postflight. After his second shift (MD1), this subject experienced no further vomiting, and discontinued drug use. The next day, discomfort was estimated to be in the 1-3 range, except when the head was moved vigorously. This pattern of discomfort was repeated at a lower level on MD4 and 5, except that nearing the end of each shift, discomfort scores rose slightly.

The other Subjects' experiences differed somewhat. Subject A did not systematically record discomfort scores in flight, but gave a detailed retrospective report shortly after landing. On MD0, his Overall Discomfort was in the 5-10 range, gradually increasing through the day, despite his use of scop/dex. This pattern repeated on MD1 until halfway through his shift, when nausea gradually increased, and he vomited, despite his use of drugs.

Subsequently, the subject vomited 3 more times, and his discomfort fluctuated between about 7 and 20 for the rest of the day. During much of his next shift (MD2-3), discomfort averaged about 10, but there was no further vomiting. On his 4th shift (MD3-4), the subject felt somewhat better (average discomfort of about 7) and discontinued drug use. Subject C experienced some queasiness near the end of his brief first shift. While eating an apple shortly before retiring, he vomited suddenly, with virtually no warning. Early in his next shift, he vomited again, also with very little warning. Queasiness persisted through much of his second shift, despite the use of drugs. Occasional discomfort persisted into his third shift, exacerbated during rapid head movements. Symptoms gradually abated, although they could still be elicited with head movements through the end of his 5th shift on MD3. This subject made relatively few numerical discomfort reports in flight, but our overall impression is that the average intensity of his symptoms was distinctly less than that of Subjects A and B. Subject D premedicated, and never experienced epigastric discomfort, nausea, or other symptoms identified as space sickness.

In addition to nausea and vomiting, symptoms and signs reported included anorexia, flatulence, belching, yawning, sensitivity to normally innocuous sensory stimuli, mild apathy, impaired concentration, and subjective warmth. Persistent headache was reported by Subjects B and C, but was probably attributable to the accelerometer headband. Retrospectively, Subjects A, B, and C noted that the dominant factor in their overall discomfort sensation was epigastric awareness and nausea, although headache and the effects of fluid shift also contributed to some degree. All reported a feeling of head fullness and congestion soon after reaching orbit which persisted throughout the entire mission. Subjects A and B used a nasal decongestant (Afrin) frequently to

combat this. All denied having difficulty with hearing, or with clearing their ears. Overall, the symptom pattern was qualitatively similar to that seen in the same individuals in the acute preflight motion sickness tests (Oman, et al, 1984), superimposed upon the physiological effects of weightlessness, except that: a) Prodromal nausea before vomiting was usually brief or absent for Subjects A and B. b) Pallor was not usually apparent. Subjects A and B checked for facial pallor change on several occasions, but observed it only once in Subject B when his sickness was intense. c) Only Subject B reported cold sweating, and this was "cold, clammy hands". d) Drowsiness was not conspicuous. e) Subject B experienced a persistent, uncomfortable feeling of stomach elevation, occasional hiccuping, abdominal soreness, and subjective difficulty in burping, as if there was a gas bubble in the middle of his stomach. However, we believe each of these apparent differences in symptom pattern observed (a-e) can be reconciled on the basis of arguments described below:

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"Sudden" vomiting with only brief prodromal nausea has been occasionally reported on earlier missions (Homick, et al, 1984). This has lead to (unpublished) speculation that vomiting in space sickness usually has no prodrome, and that therefore the etiology of vomiting in space sickness must somehow be totally different than in motion sickness. However, we believe several facts argue against this view. First, all 3 symptomatic subjects did report prodromal subjective discomfort prior to emesis, as exemplified by the data in Figures 5 and 6. Second, "avalanching" of symptoms is characteristic of other prolonged forms of motion sickness. We have found that after laboratory motion sickness is well established by periods of prolonged stimulation, if the stimulus is then temporarily removed, and the subjects are allowed to recover until nausea disappears, subjects are demonstrably more sensitive when the stimulus is reapplied (Oman, 1982a; Bock and Oman, 1982). Unless a long rest period is allowed, nausea reappears with a very short latency and symptoms then increase more rapidly than they did in earlier trials. We refer to this increase in stimulus/response sensitivity as the "sensory conflict hypersensitivity" of prolonged motion sickness. Sudden vomiting is typical of prolonged seasickness as on ocean liners, where "vomiting is very often projectile in character, and there may be little or no nausea preceding" (Desnoes, 1926). Maitland (1931), reported that in 108 seasickness cases 34 vomited without reporting nausea first. The majority of our Spacelab crew's preflight susceptibility testing was in short duration testing. Their responses to these short duration tests was largely the basis upon which they judged their "normal" prodromal pattern. Finally, all our subjects were highly motivated

individuals, and although we believe they were always candid in reporting, it is possible that their preoccupation with inflight tasks could have masked their perception of sickness intensity to some extent.

Pallor and cold sweating are consistently seen in acute laboratory motion sickness, were observed in most of these subjects in our preflight motion sickness tests, and have been reported by cosmonauts (Matsnev, et al, 1983). However, W. Thornton (personal communication) has also observed that pallor is not prominent in space. We suggest that several factors may have contributed to the virtual absence of these signs among symptomatic SL-1 crewmembers: First, the intensity of sweating is notoriously dependent on environmental factors. The Spacelab module air was cold (approx. 68 deg. F), dry, and moving. The sleeping area was also subjectively cold during the first two days. Second, we believe that the facial plethora and edema of fluid shift could at least partially mask the visible effects of closure of precapillary sphincters in the dermal circulation. For example, if venous pressure is somewhat elevated early in the mission, venous backfilling may prevent dramatic changes in dermal vessel size and net skin color. If so, electro-optical instrumentation more sensitive than the human eye may be required to document pallor changes in weightlessness. Finally, pallor and sweating may simply be less prominent in prolonged motion sickness. In Maitland's seasickness study, pallor was seen in only 32% of the cases, and hot or cold sweating in only 24%.

Graybiel and Knepton (1976) have noted that in prolonged motion sickness, a "sopite syndrome" consisting of drowsiness, yawning, disinclination for work, either physical or mental, and lack of participation in group activities are frequently present. However, they noted that in space sickness on Skylab, fatigue was often absent during the first days in weightlessness, perhaps because of anti-motion sickness drug use. On Spacelab-1, most of these same symptoms were observed, but drowsiness was also absent. Drowsiness may have here also been cushioned by drugs, and by the frequent interactive voice communication with the ground required to run the experiments.

Spacelab Subject B reported continuing uncomfortable stomach elevation sensation and desire to burp more frequently. Some cosmonauts have reported "an unpleasant sensation of heaviness in the epigastric region, and a feeling of elevation of the stomach in the early stage [of sickness]" (Matsnev, 1980). One might expect some rostral shifting of the abdominal organs in weightlessness, because the stomach and intestines are mechanically suspended by the omentum and mesentery. A thoracic shift of interstitial fluid might also contribute to a subjective sensation of stomach elevation. Under 1-g conditions, gas introduced into the stomach by swallowing or digestion will tend to rise to the fundus and esophagus, and be relieved by burping. However, in weightlessness, we have speculated there may be a tendency for bubbles to remain trapped in the stomach, cause a feeling of distention and desire to burp, and when burping does occur, to produce gastro-esophageal reflux ("wet burping"), and sensations of heartburn and stomach discomfort in some subjects (Money and Oman, 1983). Crewmen on previous NASA flights have occasionally reported "wet burping". However, our Spacelab subjects were definite that they experienced true vomiting, which involves forceful contraction of the abdominal muscles and diaphragm (Money,1970), and not just passive burping. Although Subject B was among several who frequently reported "substernal pressure" and "constricted feelings in the chest" in our motion sickness tests on earth, he recalled the gastric sensations as being different in space, since he had no feeling of elevation or

difficulty burping on earth.

The role of abdominal afferents in motion sickness in motion sickness has historically been controversial. Abdominal gas and overeating are familiar causes of stomach discomfort and nausea. Gross distention of the stomach or duodenum by very high pressures (Brown, 1963) can trigger vomiting. Vestibular and/or visual stimulation has been well identified as a sufficient condition for vomiting in motion sickness. There is laboratory evidence that visceral GI afferents play no necessary role in motion sickness (Money, 1970; Reason and Brand, 1974). In acute laboratory experiments, "gut" factors such as time since last meal and amount eaten have been consistently found not to exert any dramatic effect on motion sickness susceptibility. However, in comparison, prolonged motion sickness has been much less extensively studied. We speculate that in prolonged sickness, subjects may become more sensitive to all potentially nauseogenic stimuli once sickness due to vestibular and visual factors is well established. If so, afferent stimulation due to fluid shift and/or gas trapping could be a synergistic factor in certain cases of space sickness. Nevertheless, it seems to us unlikely that abdominal afferents consistently play a major role, since only Subject B complained of uncomfortable abdominal sensations. Head movements and various other orientation sensory cues had a much more readily identifiable role in determining the time course of nausea and vomiting, as described below:

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2. Stimuli for Space Motion Sickness:

2.1 Head Movements: The 3 symptomatic subjects unanimously identified head movements as the dominant stimulus for space sickness. They noted that the strong relationship between head movement stimuli and an increase in discomfort or nausea response was abundantly clear after symptoms had become well established. Motion on or about any axis was judged provocative. Subject B experimented with specific head movements, and found pitch movements particularly provocative on MD0. He noted that eventually he became so sensitive to head movements that he was unwilling to make any pitch head movements at all, and made only limited movements on other axes. However, three days later during the MD3 Symptom Comparison Test, rolling movements were ranked most provocative and disorienting, followed by pitch, and then forehead to knee movement, with yaw motion least provocative. Subject C performed the first few forehead to knee head movements of the Comparison Test on MD3, and quickly stopped because he found them notably provocative. On MD3, both subjects ranked

the eyes open protocol more provocative than eyes closed.

All 4 subjects said they deliberately attempted to restrict their head movements to some degree from the very start of their time in weightlessness. Nonetheless, the activation and experiment activities intrinsically required a good deal of physical motion. Head acceleration data from Subjects A and B documented how these individuals were compelled to limit their head movements in a manner apparently proportional to symptom intensity: For example, Figure 7 shows Subject B's RMS head pitch acceleration over successive 15 minute intervals plotted against Mission Elapsed Time (MET) for his first hours on orbit. Until about MET 2.0 hr, all crewmen were working in the mid-deck. Subject B reported he was moving about conservatively, but with no specific restrictions on head movement. Shortly after first entering the Spacelab (2.4 hr MET), he became symptomatic, and for the next hour "somewhat" restricted his head movements. Interpolated Overall Discomfort scores corresponding to the end of each 15 minute data interval plotted in Figure 5 are shown in Figure 8. Prior to 3.7 hr MET, RMS pitch acceleration varied over a wide range (mean 5.6; maximum 10.3 rad/sec squared). However the subject then experienced a crescendo of symptoms culminating in a vomiting episode. Although he felt better immediately and returned to his tasks, Overall Discomfort remained in the 8-12 range. Thereafter, RMS pitch accelerations averaged only 3.2 rad/sec squared, and rarely exceeded 5 rad/sec squared. The difference in the mean RMS pitch accelerations before and after the 3.7 hour symptom avalanche is significant at the 0.001 level. Although the yaw acceleration data had a generally similar character, the decrease in pitch RMS acceleration with discomfort was particularly prominent, which supports subject B's comment (at 7.2 hr MET) that "pitch axis seems to be by far the most provocative". RMS roll axis

accelerations were usually in the 1.3 rad/sec range, and correlated highly with yaw, probably because high acceleration rolling motions were also very rarely made, and the roll accelerometer axis was tilted up (see Methods).

In Figure 9, Subject B's RMS pitch acceleration data (from Figure 7) is cross plotted against Overall Discomfort data (from Figure 8). In preflight training with prism goggles, Subject B had frequently noted: "when symptoms are in the 0-5 range on the discomfort range, you can press on, but when you reach the 8-12 range, it becomes definitely time to slow down" because of concern about uncontrolled symptom avalanching. His strategy for limiting his head movements on MD0 was influenced by this experience. In an effort to reduce his vomiting incidence still further, he adopted a slightly different strategy next day: "Day 2, I picked up the time course of what was going on, and realized that if I went to a 12, I'd better stop right there. I could go between an 8 and a 12. If I hit 12, it was [time to absolutely] stop and just sit there awhile....I guess I became more sensitive to the change [in symptom intensity]. You allow for the time lag [in symptom development. I began to use more] anticipation". On his third shift, however, he felt well enough to report "head movements don't seem to be much restricted".

Similar head movement data was also obtained from Subject C. His overall discomfort was not frequently reported, perhaps partly because his discomfort was lower than Subject B's between emesis episodes. This subject noted he restricted his head movements to some extent through the middle of MD4.

Figures 10 and 11 show pitch axis data as sampled over the entire mission for Subjects B and C, respectively. The general trend is toward increasing activity

with time. As one might expect, the 15 minute RMS scores seem to show not only a higher mean, but greater variability (presumably reflecting the varying physical task demand) when the subject is feeling better, and therefore isn't severely limiting his head movements. To examine overall trends without confining the analysis specifically to pitch data, we computed composite "angular" and "linear" RMS acceleration indices for each subject and 15 minute period by summing the 3 angular and 3 linear RMS acceleration scores, respectively. Both the angular and linear activity metrics thus formed are significantly increased (at the 0.005 level, t test) after MD3. The mean value of both metrics was higher for Subject C than for Subject B, who we believe was more symptomatic. However, we are reluctant to draw inferences from such comparisons between subjects until our head movement data base is larger, and includes asymptomatic subjects.

In interpreting the head acceleration data, we considered, but rejected a contrary hypothesis that reduced periods of head movement somehow cause increased symptoms, because it was clear from subjects' reports that the presence of symptoms compelled them to limit their movements. Readers should also note that other measures of head movement such as velocity or displacement amplitude correlate with head acceleration amplitude measured by our accelerometers. Hence it would be incorrect to conclude that RMS head acceleration itself is the parameter being limited by the subjects, or necessarily the best metric of the stimulus for sickness.

Taken together, the evidence from the Symptom Comparison Test and the objective head movement recording are consistent with earlier reports that head movements in weightlessness are provocative. Once symptoms become established, head

movements must be held to a minimum to prevent further avalanching. When emesis occurs, there is a likelihood that the subject will feel better for a time. The shortest time observed between vomiting episodes was approximately 50 minutes (Subject B, MD0). There was some evidence that pitching head movements were most provocative, an observation which is consistent with some previous reports (Matsnev, 1980; Thornton, 1983). This may indicate that the lack of a confirming otolith cue during head pitch is particularly provocative. However, it was apparent that yawing head movements are also provocative, and that the provocative ranking of the different types of head movements attempted in the Symptom Comparison Test changed with time for Subject B. The head accelerometer data indicates that RMS head accelerations are higher in yaw and pitch than in roll. It may be that adaptation to space sickness occurs first on head axes about or along which large amplitude movements are most frequently made.

2.2 Ambiguous Static Visual Cues and Reorientation Episodes: Even in the brief weightlessness of parabolic flight, visual, touch, and pressure cues have long been known to play an important role in spatial orientation (Graybiel and Kellogg, 1967). When subjects are asked to describe the direction of subjective "down", a general tendency to feel that it lies near the direction of one's own feet has been reported, although proprioceptive factors also can influence one's impression of the aircraft's orientation with respect to the earth (Lackner and Graybiel, 1983).

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In parabolic flight training on the NASA KC-135 aircraft using ourselves and Spacelab crews as subjects, we have repeated these experiments. Subjects consistently reported that the notion of a "down" with respect to the earth is irrelevant in the almost windowless cabin, and how the subject described his sense of "down" depended very much on how questions were phrased. Our subjects often said that the use of the word "down" - which most felt carries a strong

gravitational connotation - was inappropriate to completely describe their sensations. They were intellectually aware of the actual orientation of the aircraft with respect to the earth, but said it had little to do with their subjective sensations once in weightlessness. Consequently, they preferred to use other terms such as "visual down" or "subjective floor" to describe their sensations.

If a subject (observer) gradually rolled upside down with respect to the cabin (the "Neider" position described by Graybiel and Kellogg), frequently the ceiling of the aircraft beneath his feet suddenly subjectively became a "floor", and he no longer felt subjectively "upside down". The visual environment then was somewhat unfamiliar, since the location of items seemed strangely left/right transposed from that remembered. Catching sight of inverted familiar objects and/or making a cognitive effort frequently could reverse the illusion, such that the true "floor" is again perceived as such.

To explain this phenomenon, we note that in the absence of gravity, one must orient and move about with reference to the familiar "ceiling/floor" "left side/right side" and "forward/aft" dimensions established by visual recognition of the aircraft interior. We believe that when a scene is viewed from an unfamiliar angle in weightlessness, fundamental symmetries in the visual scene can create an ambiguity in the perceived identity of surrounding surfaces. In life on earth, this ambiguity is not present, because the direction of gravity always defines the direction of the subjective floor.

Graybiel and Kellogg (1967) termed the sensations produced by this maneuver an "Inversion Illusion". However, this term is not entirely appropriate to describe our experiences, because the actual subjective sensation produced was not of "being upside down" with respect to the subjective floor. We prefer to reserve the term "Inversion Illusion" to refer to the subjective sensation that both the observer and his visual surround together are "upside down", a different illusion which has also been described in the Soviet literature (eg. Matsnev, et al, 1983), and which was also experienced by one Spacelab 1 Subject (see below). Unfortunately, the term "Inversion Illusion" has been inconsistently applied in the literature to both types of illusions.

We experimented further with these illusions in different body orientations with respect to the cabin. We noted a general tendency to assume that when the subjective "floor" changes, it generally becomes that cabin surface which is closest to being beneath the observer's feet and parallel to the left/right head visual axis. The illusion was more readily produced if the observer looked down at his own feet or body, or placed them in contact with the subjective "floor". If the observer floated very close to featureless cabin surface with body parallel to it, there was a tendency to perceive the surface as a subjective wall, (even if it was actually a ceiling or floor), perhaps because the familiar visual experience in everyday life corresponds. Checklists or a simulated instrument panel taped flat to the subjective "wall" in a readable orientation strengthened the illusion, and set the direction to the subjective "floor". In any situation, a change in gaze angle or scene content was sufficient to trigger a change in subjective orientation. For example, if the observer simply viewed another person who was floating nearly horizontally or inverted with respect to the actual cabin floor, and other visual cues were ambiguous (as when the observer himself is in an inverted orientation) the observer often suddenly felt that it was he himself who was tilted, so that the wall or ceiling of the

aircraft closest to being in the direction of the seen person's feet is perceived as the subjective floor. If the observer then looked away at other recognizable objects (seats, etc.) tied to the actual floor of the aircraft, the illusion often would reverse. When they occur, these visual illusions have a paradoxical aspect, because they involve a subjective change in self-orientation (typically 90 or 180 deg) with respect to the perceived directions of the floor, walls, and ceilings which takes place without any corresponding vestibular cue to body movement. They are somewhat analogous to well known figure reversal illusions (e.g. the Necker cube), except that what is changing is not the subjective orientation of the object, but one's own self-orientation with respect to the perceived surround. To distinguish them from "Inversion Illusions", we here refer to them simply as "visual orientation illusions", and sudden changes or uncertainty in perceived orientation associated with them as "visual reorientation" episodes.

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Because visual reorientation episodes involve a change in subjective orientation without motor commands and confirming vestibular and proprioceptive cues, we hypothesized that they would be potentially provocative. Since our Spacelab-1 subjects were familiar with these illusions in parabolic flight, we asked them to note whether they also occurred in orbital flight, and the extent to which they were associated with symptom onset.

After the Spacelab-1 mission, all crewmen reported experiencing such orientation illusions occasionally throughout the flight. Visual scenes typical of those which sometimes produces visual orientation illusions and reorientation episodes are shown in Figures 12-14 from the observer's point of view. Reorientation episodes were reported to sometimes be provocative, although this was noted only early in the mission by crewmen who were already experiencing some symptoms. Because they had previous experience with the illusions, and believed they might be potentially provocative, the symptomatic subjects deliberately tried to maintain an upright attitude with respect to the Spacelab and Mid-Deck floor whenever practical. Subject B commented that "[early in the mission when I was sick] I really needed a good vertical feeling, a good optical down. It was really distressing when [at 0/01:50, another crewman] came floating into the

[Spacelab] module upside down and tumbling and things.. I felt like I needed a real visual down, and it was the floor.." At 0/03:45, Subject B briefly assumed an inverted attitude. Very shortly thereafter, he vomited for the first time. At 3/11:07 he noted "For the first several days, it was very important to maintain myself upright with respect to Spacelab. Today...even without drugs I was able to obtain any orientation I felt like".

The symptomatic subjects noted that early in the mission, they did not enjoy traveling through the tunnel connecting the Spacelab with the Orbiter airlock and thence the mid-deck stowage/sleeping/eating/toilet area. The tunnel (Figure 14) had no well defined floor, walls, or ceiling, and only one dominant axis of symmetry. Its small diameter required crewmembers to float through it head first in a manner impossible to practice preflight. When traveling through, it was easy to lose track of orientation, and to be surprised at the orientation of Spacelab or the airlock when emerging. Subject C recalled a strong aversion to tunnel trips in postflight debriefing. His two vomiting episodes both occurred within a few minutes of a trip through the tunnel.

Several subjects commented that veridical orientation was also sometimes difficult to maintain in the Mid-Deck area. Subject B noted that he usually entered the mid deck from the tunnel facing the true ceiling, and perceived the true ceiling as the floor, and felt that he was looking "down" into a well. Maintaining orientation while looking out of the lower sleeping cubicle was also a problem: Subject B reported that "my bunk was the bottom one, and [it was designed so that the two of us who used it had to attach our sleeping bags to the ceiling of the sleeping cubicle, rather than the floor, so that we hung upside down like a bat hanging from the ceiling. I found that distressing for

the first couple of days. I'd [slide open the door and] look out there in the morning and I'd see the orbiter [mid-deck area] all upside down. That was very disconcerting". Subject C recalled the same experience.

In the Spacelab module, visual orientation illusions were less frequent. Subject B noted while working on the slanted upper panels of Spacelab racks, that he occasionally spontaneously oriented to them as "walls" and was therefore startled to see the lower panel slanting out beneath him. When entering the Spacelab module, he never experienced a reorientation illusion spontaneously, and all subjects noted that reorientation episodes never occurred spontaneously when everyone was working upright in Spacelab. The crew had trained for several years in a high fidelity 1-G Spacelab mock-up, and they felt very familiar with it. However, later in the mission, Subjects B and D experimented with deliberately entering the Spacelab from the tunnel upside down, or rolling inverted in the Spacelab module, and found they could volitionally make the ceiling the subjective floor when a second crewmember also assumed the inverted position. Subject B recalled experiencing a ceiling as floor reversal when he and another crewmen stood on the ceiling, and looked "down" at the earth though a window at their feet. Thus, although reorientation illusions can occur spontaneously, they can also be created with simple cognitive effort under appropriate circumstances.

On earlier Shuttle missions, crewmen have occasionally reported that if the earth was seen in an unfamiliar or unexpected orientation, that it could produce an increase in symptoms. In at least one case, it may have provoked vomiting. On Spacelab 1, some of our subjects occasionally experienced visual reorientation episodes when they looked at the earth, or back inside the

vehicle. Subject B noted that he strongly preferred to orient himself when looking outside so that the earth was in his lower visual field, and space was above. None of our subjects recalled that these episodes were provocative, but said that they deliberately avoided looking out of the spacecraft while symptomatic on their first few days in orbit.

On Spacelab-1, visual orientation illusions were experienced occasionally throughout the mission. One might expect that as crewmen became more experienced working in agravic attitudes in the visual environment, and seeing others working this way, the tendency for visual orientation illusions to occur spontaneously might diminish. However, there are known to be basic limitations on human abilities to mentally turn inverted visual objects and recognize them (Howard, 1982). Whether illusions gradually became harder to get due to experience in weightlessness was unclear.

Visual illusions have been reported previously on Soviet and Skylab missions (Matsnev, et al, 1983; Cooper, 1976) which we believe are similar to those experienced by our subjects. We suggest that the provocative aspect of reorientation episodes is not subjectively apparent to asymptomatic subjects because the episodes are brief and infrequent. We suspect that head movements are most likely the dominant cumulative factor driving sickness intensity above threshold levels. We hypothesize that as a subject begins to experience symptoms due to a prolonged interval of head movements, he also becomes more sensitive to other stimuli. Reorientation episodes then can produce twinges of nausea, and in some circumstances deliver a "coup de grace", triggering an episode of emesis. After several days on orbit, most subjects gradually adapt to the head movement stimulus, and the provocative nature of reorientation

episodes should become once again insensible. The tendency to experience such illusions in a particular visual environment likely will depend on the observer's previous visual experience both in training and in flight and perhaps also on other personal characteristics. Whether susceptibility to these illusions also covaries with some of the recognized 1-G measures of static "visual field dependence" such as the "rod and frame" test (Witkin and Asch, 1948) or with measures of dynamic visual/vestibular interaction, such as circularvection latency (Young, Shelhamer and Modestino, this issue) remains to be determined. We did not test our subject's reactions to controlled static visual scenes in orbit.

Subject B also reported that after reaching orbit, he experienced what we consider a true "inversion illusion" in the mid deck: The orbiter cabin was inverted during the launch and ascent, and the crew hung in their straps despite the thrust of the engines. After achieving weightlessness, Subject B was surprised to find that he continued to have an illusory sensation that both he and the Shuttle were hanging upside down, even though his feet were toward the floor. This perception persisted continuously, despite his occasional deliberate efforts to reverse it by pulling himself down into his seat, a method previously reported helpful by Cosmonauts (Graybiel and Kellogg, 1967). The illusion disappeared only after Subject B unstrapped from his seat and moved about the mid deck area an hour later. First symptoms were noticed shortly thereafter. We believe that headward fluid shift and gravitational unloading of the saccular otolith in weightlessness combined with the relatively unfamiliar visual environment of the mid deck to promote a sense of inversion. When such inversion illusions occur, they may have a paradoxical aspect, since one seems simultaneously both right side up and up side down, a conflict only partially

resolvable by assuming the spacecraft and observer are somehow hanging inverted. Based on the sensory conflict notion, we therefore hypothesize that inversion illusions are continuously provocative to a degree, in contrast to momentarily provocative visual reorientation episodes. Subject B's inversion illusion plausibly might have contributed to his sickness, although the temporal cause/effect relationship was not fully established.

2.3 Tactile/Proprioceptive Cues and Passive Body Restraint: Our three symptomatic subjects reported that when surface contact force was passively applied to provide compelling touch and pressure cues indicating that the body was not moving, symptoms were subjectively ameliorated. Subject B first experimented with the use of a harness and bungee cords (Watt and Money, this issue) which pushed him toward the floor with an adjustable static load of up to 1-g. While symptomatic at 0/10:20, he noted that "it appears that putting tactile cues on did tend to help to some extent... it appears that free floating with a little bit of tactile feeling on the feet is probably about the most beneficial; if I get (the bungees) up too tight, it doesn't feel right, and if you're just floating, it doesn't feel right either, but a little bit of tension on the feet seems to help me feel better". However, after further experience, he reported that a procedure suggested by Subject A was better, in which he "wedged" his body in between the aft endcone of the cabin and the last experiment rack. "I had good pressure on both sides of me to give me good stability, and it wasn't just against my back. And I was out of the volume. One of the most distressing things seemed to be that big volume. The feeling of tactile cues around your body, that you are not floating off into space..You don't need to go to the [trouble] of putting on the harness and attaching the bungees..." Subject B experimented after a provocative test (3/11:00) to see

if the same effect could be achieved if he actively applied the tactile forces himself. While feeling "about a 5", he noted that "it's usually more provocative trying to hold yourself down against something flat rather than it is just to wedge yourself into the corner... I try to press myself down into the sitting position, and it feels very awkward and uncomfortable and provokes slight stomach awareness." None of our subjects tried strapping into a spacecraft seat. However, Subject C recalled that he immediately felt better when he strapped into the Body Restraint System seat used in the European Vestibular Experiments. Subjects A and B also sought relief in their bunks by bringing their knees up to their chests, and pushing them against the door, and using a velcro head restraint strap.

If our subjects' experiences are representative, then appropriately designed body restraints may be of value in alleviating symptoms of space sickness. The design objective apparently need not be to provide an artificial "gravity" cue so much as to provide comfortably firm pressure on the trunk, upper legs and head. On this basis, we expect that the elastic neck restraint cap ("NPSA") and the foot insole counterpressure device and the "Penguin" elasticized suit evaluated by Soviet cosmonauts (Matsnev, et al, 1983) should be less effective than "wedging in". These devices do not prevent body movement with respect to the spacecraft.

3. Effectiveness of Pharmacological Countermeasures: All 4 of our crewmen took drugs over a 2-4 day period, and 3 experienced symptoms, so at first glance, one might conclude that the drugs were relatively ineffective. However, several observations suggest that the drugs may have had some beneficial effect: First, the 3 symptomatic crewmen had the distinct impression that the drugs they took

(with the exception of metoclopramide) were helpful. One subject felt he could tell when his scop/dex was wearing off by discomfort increase. Second, data on when vomiting episodes occurred relative to anti-motion sickness drug use (Figs. 3 and 4) show vomiting was less frequent when drugs were taken: The three subjects took scop/dex frequently over a 2-4 day period. If experience in 1-g is a guide, scop/dex is most effective in the period 3/4 hr until 4 hr after administration. Three out of 4 of Subject A's vomiting episodes, and 5 out of 6 of Subject B's episodes (see Figs. 3 and 4) took place outside of this period of presumed effectiveness. Subject D, who also used scop/dex, was asymptomatic the entire time. Subject C had not taken any drugs prior to his 2 vomiting episodes on MDO. He subsequently took promethazine/ephedrine once at the end of his second full working day. His impression was that it "certainly had some effect".

In evaluating drug effectiveness, it is important to keep in mind that the protection conferred by a drug is a matter of degree, and no drug has been found for motion sickness, let alone space sickness, which acts as a "silver bullet", totally preventing sickness in everyone. Anti-motion sickness drugs are commonly recognized as being more effective in prophylaxis than in treatment; of 3 who became sick, 2 had not premedicated. Our conclusions on drug efficacy could be more clearly drawn were it possible to adopt a double blind approach to drug evaluation. However, even allowing for the possibility of a placebo effect, we believe that our 3 subjects' experiences are encouraging. Considering the number of scop/dex doses taken in succession, it is also noteworthy that significant side effects (other than dry mouth) were not reported.

Neither of the subjects who tried metoclopramide saw any evidence that it was effective. Subject B felt the drug may have in fact increased his stomach discomfort. Metoclopramide is a dopamine antagonist which increases the amplitude of gastric contractions and the tone of the esophageal sphincter, relaxes the pyloric sphincter, and increases peristalsis of the duodenum. Its conventional clinical use is to stimulate gastric emptying. However, its use against space sickness has been advocated by several workers, and it was informally evaluated on the previous Shuttle flight. It should be noted that the effect of Reglan on motility can be abolished by anticholinergic drugs, so taking Reglan in combination with scopolamine may have compromised Subject B's drug trials to some degree.

4. Pre/Postflight Motion Sickness Susceptability Tests: Rank order results of the 6 preflight motion sickness tests (see Methods) are shown in Table I below:

TABLE I
Rank Order Susceptibility Scores:
6 acute preflight motion sickness tests

Subject	PAM-A	PAM-B	KC-135	VVI	CSVT	CSSI	Overall
A	2	2	3.5	3.5	2	2	2
B	4	4	3.5	2	3	3.5	4
C	3	3	2	3.5	4	3.5	3
D	1	1	1	1	1	1	1

Columns: Ranked scores where 1 is most susceptible, 4 least susceptible. Score of 3.5 indicates tie. PAM-A, PAM-B, KC-135, etc are test types. See Methods for summary of procedures. Overall is best estimate based on rank sums.

In the Prisms Test conducted in February, 1979 (see Methods), the latency time to first symptom varied from 23 min. to more than 180 minutes (i.e. no sickness). Ranked susceptibility in order of decreasing susceptibility, was A,B,C,D. Adaptability ranks showed the same order. In a repeat test (Sep 79) in which all 4 subjects used anti-motion sickness drugs, the ranked susceptibility was A,B, then C/D tied.

Overall sickness intensity on-orbit varied between individuals with time. However, the overall ranked intensity was estimated to be B,A,C,D where B's sickness was most intense, and D had no symptoms.

When tested in parabolic flight (KC-135) on the 4th day after landing using the same procedure, none of the subjects showed any symptoms whatever. Their immunity was further apparent when, after the 20 parabola head movement test, an additional 20 parabolas were flown to accomplish other experiments, and the 4 subjects remained asymptomatic, in spite of much activity while free floating.

When tested in similar fashion one year postflight, subject D showed significant symptoms, whereas the other subjects were asymptomatic. In the preflight KC-135 tests, the other subjects had experienced only minor symptoms.

In previous studies, motion experience questionaires, psychodynamic variables, and vestibular organ thresholds have generally not been found to be good predictors of motion sickness susceptibility. Positive (although occasionally inconsistent) test/retest and inter-test correlations have been found within and between some of the established acute laboratory tests for motion sickness susceptibility (e.g. Miller and Graybiel, 1970; Homick, et al, 1983) . If space sickness is a motion sickness, one might assume that the a subject's symptom intensity under operational conditions on orbit should be predictable. However, attempts to do so based on a single type of acute susceptibility test have been unsuccessful (Graybiel, et al, 1977; Homick, et al, 1984). We believe there could be at least four possible explanations for this:

1. Even if test/retest correlations are statistically significant across a

large subject population, response variability may be high enough so that it is difficult to accurately predict the result of a single trial.

2. Although short duration motion sickness tests utilizing various different types of stimuli frequently show significant inter test correlations, real differences do exist among individuals in terms of susceptibility to the various tests. A predictor based on composite results of several different types of test might have advantages.

3. Many of the tests previously proposed as predictors arguably did not employ a stimulus physically similar to weightlessness.

4. Previous studies utilized short duration motion sickness tests, which may not predict susceptibility or sickness intensity during prolonged stimulation typical of space sickness.

5. Stimulus factors are uncontrolled under operational conditions. Crewmembers are assigned different tasks on orbit, and each may take a different approach to drug use, head movement and body attitude restriction. Crewmembers who believe themselves susceptible based on ground tests might adopt more conservative head movement strategies, for example. The latter might actually produce a negative correlation between ground susceptibility predictors and inflight sickness intensity.

In planning our study, we therefore developed a composite susceptibility motion sickness ranking by exposing the same group of subjects to a selected group of different tests. The Coriolis Staircase and CSSI tests measured resistance to cross coupled angular acceleration, and were procedures similar to those used in previous attempts to predict susceptibility on-orbit. The Visual Vestibular Interaction Test measured resistance to angular acceleration stimuli during a visual fixation task requiring angular vestibulo-ocular reflex suppression. In

contrast, the PAM test stimulates primarily the graviceptive senses with a rotating linear acceleration vector. The KC-135 test created for brief periods the same physical stimuli which the crew would be exposed on orbit, alternating with periods of hypergravity, during which no head movements were made. To examine test/retest repeatability, we included some repeat trials. Since the measurements made in the various tests were different, and not all normally distributed, we utilized a nonparametric method (Kendall Concordance Test; Kendall, 1948; Siegel, 1956) to examine the inter-test correlation. This approach requires no assumptions regarding normality of data. The Kendall Concordance parameter for the 6 tests shown in Table 1 was 0.68, a value which is significant at the 1% level, indicating that there is significant agreement between the different susceptibility measures, and allowing us therefore to reject with confidence the hypothesis that the rankings were essentially randomly drawn. Based on the combined ranks, the best estimate of overall susceptibility was: D,A,C,B. That the Concordance between these 6 relatively heterogeneous tests is so high suggests that scores on these tests are largely dependent on some common physiological trait, rather than the details of the stimulus patterns used. KC-135 rankings largely resembled those in the other tests. That Subject D would be ranked most susceptible on all 6 tests is extremely unlikely to have occurred by chance. However, neither the overall susceptibility rankings nor the results of any one of the 6 acute tests came close to predicting in-flight ranked sickness intensity. Comparing observed motion sickness susceptibility and space sickness intensity rankings, the least and most susceptible subjects reversed position.

Although all 5 possible explanations for the poor correlation seen between ground and flight measures may be valid, considering our results, we suspect

that the last two factors may be particularly important. The notion that susceptibility to prolonged motion sickness is a better predictor of space sickness is tentatively supported by the results of the 2 Prism tests: Prism tests ranks were quite different than the 6 acute tests, and predicted that D would be least susceptible, and that A and B would have more intense symptoms than C and D. However, the number of subjects is as yet too small for statistical significance.

Our postflight test results indicate that residual adaptation to orbital flight renders subjects immune in parabolic flight 4 days later. That Skylab astronauts showed a 1-2 week decreased postflight susceptibility to Coriolis head movements (Graybiel, et al, 1977) suggests that this immunity may not be 0-g stimulus specific. However, when considered with previous reports of seasickness on earlier NASA flights immediately after landing in the ocean, and reports of brief post-mission "earth sickness" in the US and Soviet programs, these findings together support the view that adaptation to weightlessness may incude both environment specific and generalized components. Brief retention of environment specific 0-g adaptation may produce increased susceptibility to earth and sea sickness during the day of return. Reduced susceptibility in 1-g thereafter may be attributable to a generalized stimulus non-specific adaptation acquired in orbit. That Subject D was asymptomatic on the KC-135 after 4 days on orbit, but that symptoms appeared when tested both preflight and 1 year postflight suggests that the protective adaptation conferred by orbital flight probably fades. The Spacelab-1 crewman who flew on Skylab experienced sickness on both orbital flights, indicating that adaptation to 0-g does not confer immunity in flight a decade later.

CONCLUSIONS: In this paper, we describe 3 cases of space sickness as they occurred on Spacelab-1. We report quantitative data on the relationship between head movements and symptom intensity in 2 subjects, detailed observations on the role of visual, tactile, and proprioceptive orientation cues as additional stimuli for sickness, and data on drug use and pre/postflight motion sickness susceptibility. We believe that these findings more clearly establish space sickness as a form of prolonged motion sickness. Prior to appearance of symptoms, head movement is variable and apparently task driven. As in prolonged motion sickness on earth, symptom onset is characterized by an initial delay, and once sickness becomes established, by a tendency toward more rapid symptom crescendo than in acute laboratory motion sickness. Pallor and cold sweating are not prominent, as one might expect. Crewmen experience stuffy noses, head fullness, and other symptoms of fluid shift which contribute to overall discomfort, although largely present throughout the flight. Abdominal fullness and possible stomach gas trapping may be contributory in individual cases. Other symptoms of space sickness are those of the more familiar forms of acute motion sickness.

Head movements are a clearly identifiable stimulus for sickness. All movements are subjectively provocative, although pitch and roll movements are particularly so. We have quantified for the first time how overall discomfort magnitude estimates modulate with time over several days in orbit, and how symptomatic crewmen are compelled to limit head movements in order to prevent development of symptoms. As adaptation to weightlessness proceeds over several days, head accelerations increase in size and variability once again.

Visual cues in the weightless environment were also identified as a second

significant stimulus for sickness. When crewmen assume unfamiliar orientations, inherent ambiguities in the static visual cues used to identify the subjective "floor", "walls" and "ceiling" surfaces in the absence of gravity are more pronounced than on earth, and can trigger episodes of subjective spatial reorientation in themselves or others aboard. These episodes are different from "inversion illusions" previously reported, and correspond to illusory episodes observed by us in parabolic flight and similar reports on other missions. These episodes were experienced on occasion by all crewmen throughout the SL-1 mission, and were noted to be subjectively provocative by those having prexisting symptoms. The effective stimulus is the reinterpretation of static visual orientation cues, and does not require any motion of the head or body. Frequency of these episodes probably can be reduced if proper consideration is given to them in the design of sleeping and work areas, connecting tunnels, etc. and if "agravic" body attitudes and earth-watching are avoided when crewmen are symptomatic.

In addition to head movement and body orientation restriction, symptoms were subjectively alleviated by "wedging" the body into locations providing broad tactile and proprioceptive contact cues indicating the absence of motion. It was reported that footward loading of the body specifically to simulate earth's gravity was not necessary for this effect. That astronauts in the Mercury and Gemini programs reported no episodes of space sickness may be because when strapped into the seats of their small spacecraft, head movements and body orientations were restricted and ample surface contact cues were present. The absence of symptoms on these flights has in the past usually been attributed only to the first of these 3 factors.

Anti-motion sickness drugs used by the Spacelab crew reduced the frequency of vomiting and overall discomfort, although the possibility of a placebo effect cannot be ruled out. Symptom intensity in orbit was not predicted by a motion sickness susceptibility ranking derived from 6 acute preflight tests, although one other preflight test (prism goggles) involving more prolonged stimulation showed a rough correlation. Difficulties inherent in predicting on orbit symptom intensity from preflight tests are discussed.

Overall, our data support the view that space sickness is fundamentally a motion sickness, and is thus a very normal response to the abnormal environment.

ACKNOWLEDGMENTS We are grateful to our subjects, whose interest and professionalism made this study possible. We thank Investigators L.Young and D. Watt; and at MIT: J. Binsack, W. Mayer, R. Goeke, P. Tappan, A. Natapoff, and O. Bock; at DCIEM: R. Cheung; at NASA Johnson Space Center: G. Salinas, R. Clark, J. Evans, E. Peck, and D. Harris, J. Homick and the JSC Neurophysiology Laboratory for providing CSSI and CSVT data; The European Vestibular Experiment team, who conducted the 4th day postmission KC-135 test cooperatively with us. This research was supported by NASA Contracts NAS9-15343 and -17371, and DCIEM/Canada. Dr. Money's present address is: National Aeronautical Establishment, NRC, Ottawa, Canada. Lt. McCoy's present address is: USAF/AFOTEC/OAHF, Kirtland AFB, NM 87117-7001 USA. Opinions expressed in this paper do not necessarily reflect those of USAF.

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FIGURE CAPTIONS

Figure 1. SL-1 Crewmember wearing Acceleration Recording Unit. Angular and linear accelerometer triads worn behind head send data to belt mounted digital tape recorder on left hip via battery/electronics module behind back.

Figure 2. Amplitude histogram of pitch angular accelerometer output for 15 minutes of data sampled at 100 Hz. Subject C; starting at MET 0/02:23. Standard deviation of 4.3 rad/sec squared estimates Subject C's RMS pitch angular acceleration over the 15 minute period ending at MET 0/02:44. (Mean = -1.68 rad/sec squared, largely due to accelerometer zero offset. 90,000 samples. Record/playback error rate 0.2%. Histogram abscissa range 150 rad/sec squared. Bin width 1.14 rad/sec squared.)
(Note to layout: please size this figure so that labelling of abcissa is readable.)

Figure 3. Pattern of anti-motion sickness drug use on SL-1, first day in orbit for Subjects A - D. Diamonds: 0.4 mg scopolamine/2.5 mg dexedrine. Triangles: 25 mg promethazine/25 mg ephedrine. Arrows: emesis Black bars: estimated interval of maximal drug effectiveness.

Figure 4. Pattern of drug use, second day in orbit. Details as in Figure 3.

Figure 5. Overall discomfort vs. MET for Subject B. First day in orbit. Ordinate: 0 - 20 magnitude estimate. 10 is halfway to vomiting. A score of 20 indicates emesis. Circles: in orbit reports. Diamonds: time of scop/dex drug dose; bars: estimated interval of maximal drug effectiveness

Figure 6. Magnitude estimate of overall discomfort vs. MET for Subject B. Second working shift in orbit. Triangle: time of metoclopramide dose. Additional details as in Figure 5.

Figure 7. RMS Pitch Angular Acceleration vs. MET for Subject B from 0/01:04 through 0/08:34.

Figure 8. Overall discomfort estimate vs. MET for Subject B. Time period as in Figure 7.

Figure 9. Overall discomfort estimate vs RMS pitch angular acceleration for Subject B over time interval of Figures 7 & 8.

Figure 10. RMS pitch angular acceleration ("Pitch Index", rad/sec squared) vs. MET (in days) for Subject B during his first week in weightlessness.

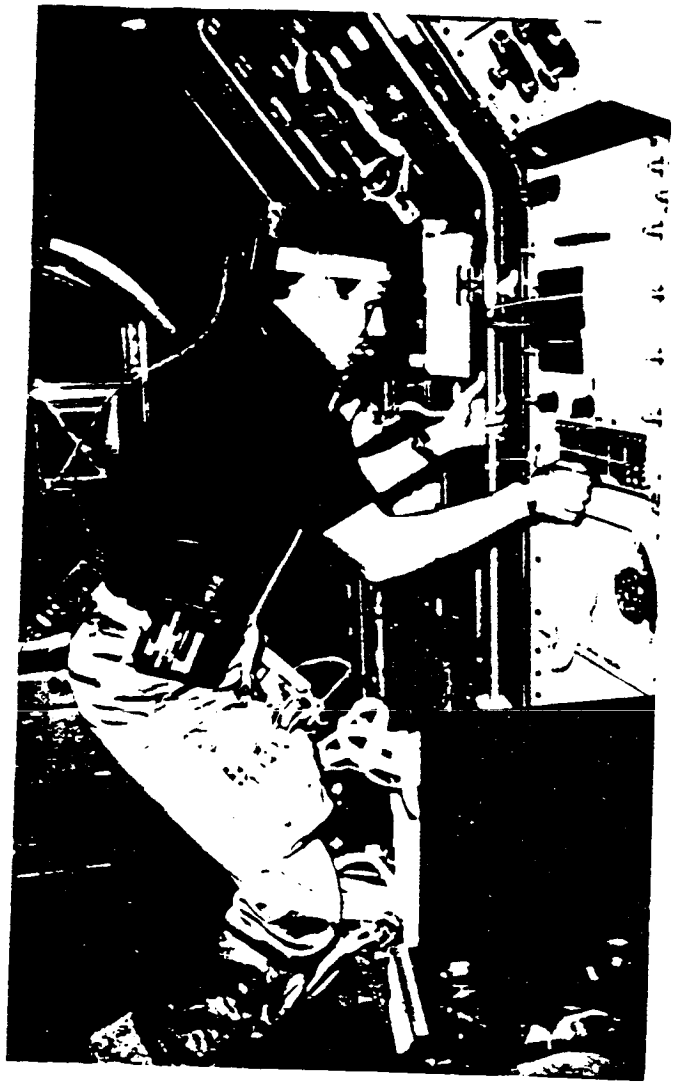
Figure 11. RMS pitch angular acceleration vs MET for Subject C. Details as in Figure 10.

Figure 12. Visual Orientation Illusion: When an observer views another person floating with feet towards the Spacelab ceiling while himself in a similar orientation, the observer may suddenly feel that the true floor has subjectively become a "ceiling", and so no longer feels "upside down".

Figure 13. Visual Reorientation Episode: The visual orientation illusion of Figure 12 typically reverses when the people in view reassume a "normal", feet

reorientation episode, and suddenly feels "upside down".

Figure 14. Interior view looking forward of the tunnel connecting Spacelab with the Shuttle Orbiter mid-deck airlock. Travel through the tunnel could be disorienting.



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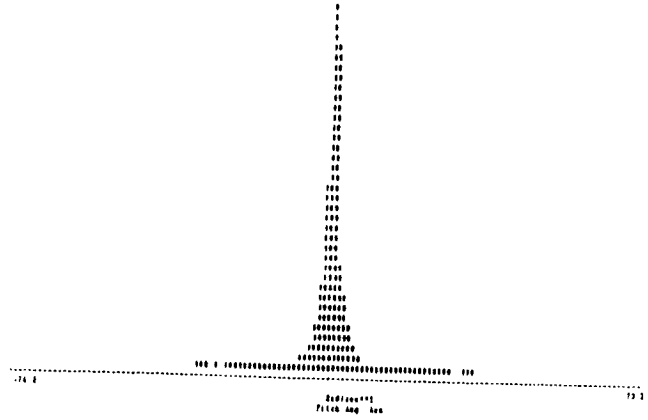

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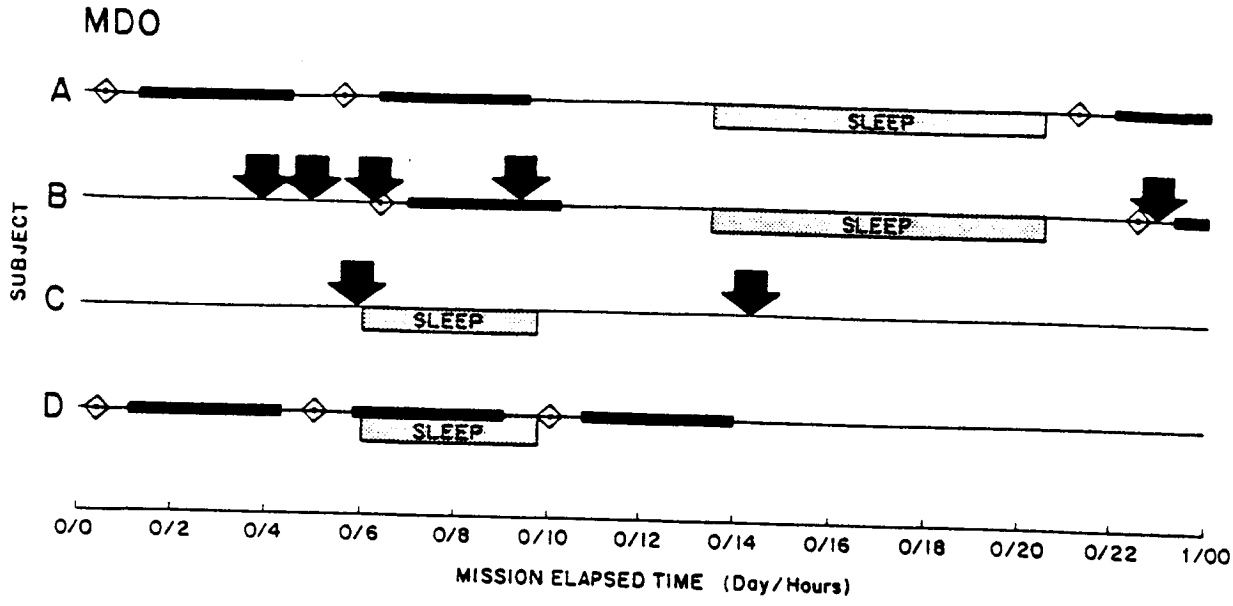

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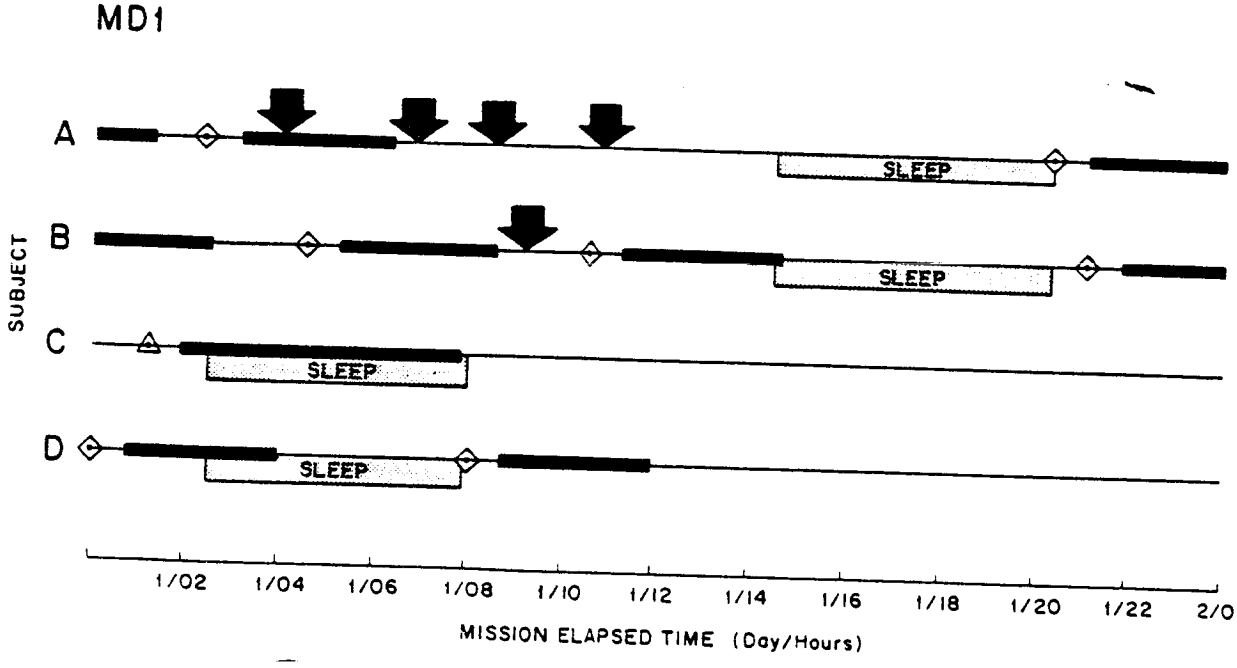

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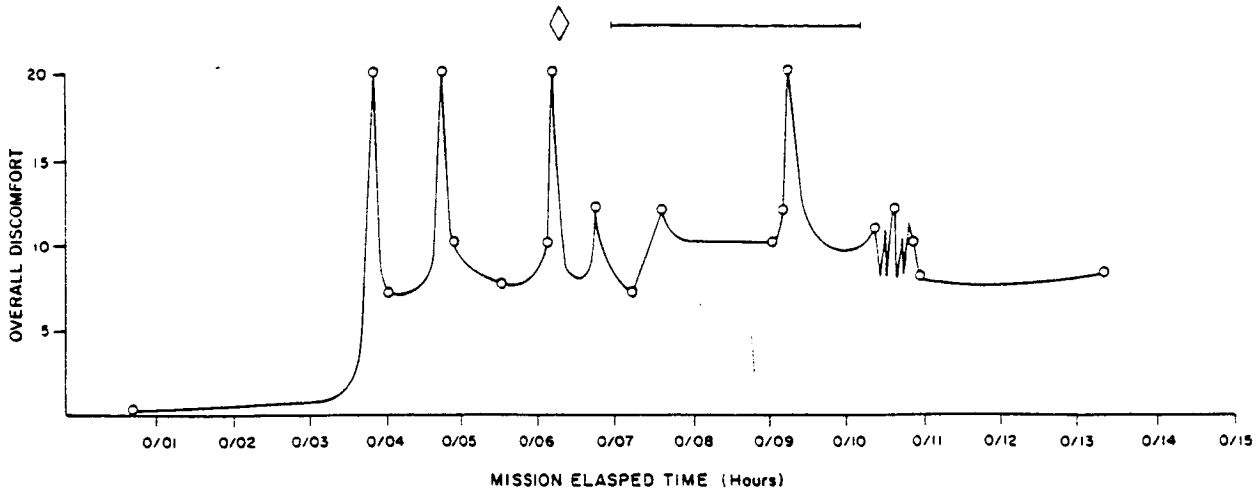

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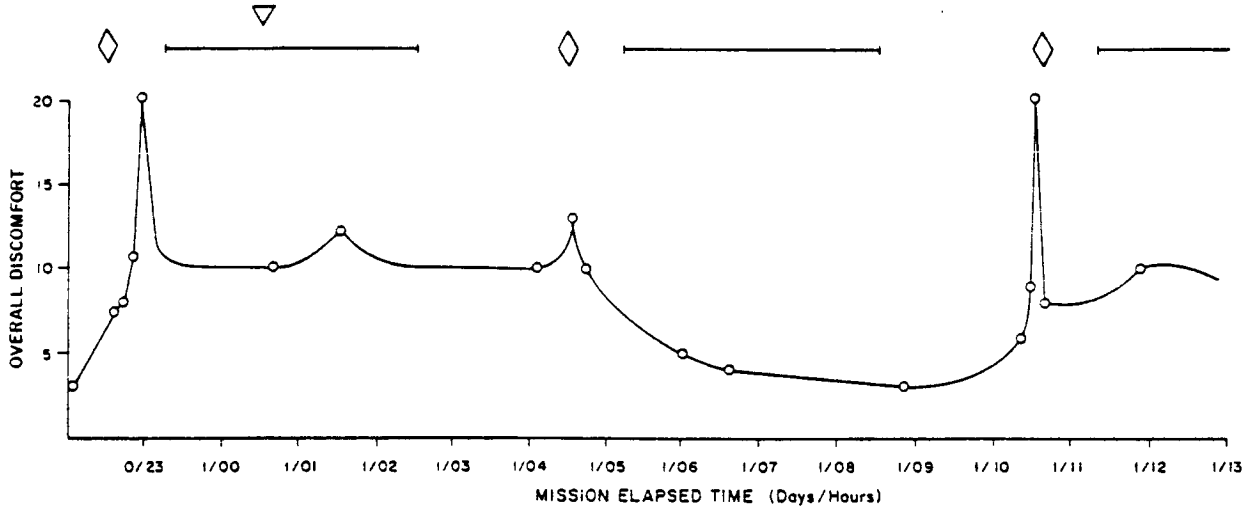

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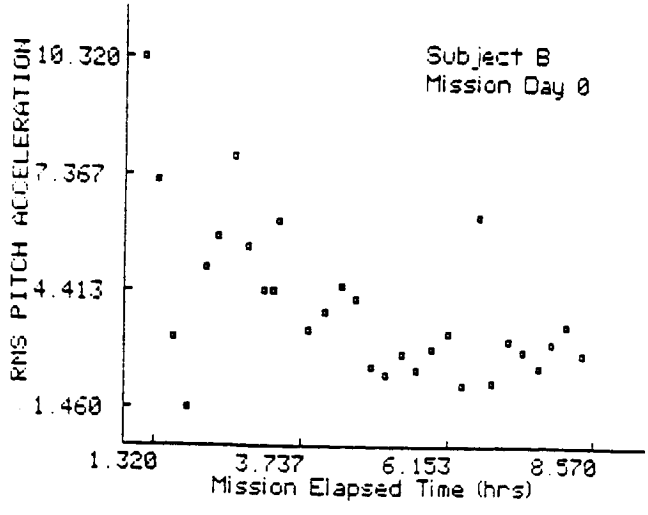


Figure 7. RMS Pitch Angular Acceleration vs. MET for Subject B from 0/01:04 through 0/08:34.

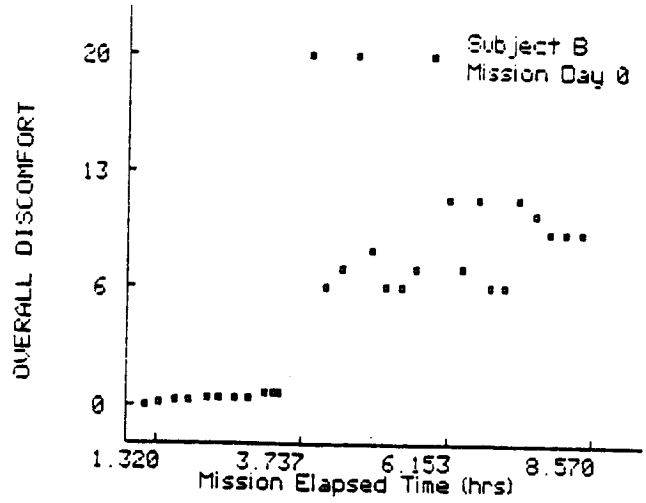
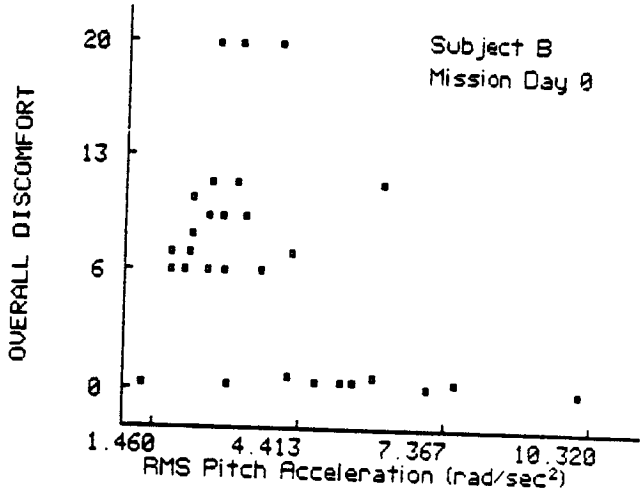


Figure 8. Overall discomfort estimate vs. MET for Subject B. Time period as in Figure 7.



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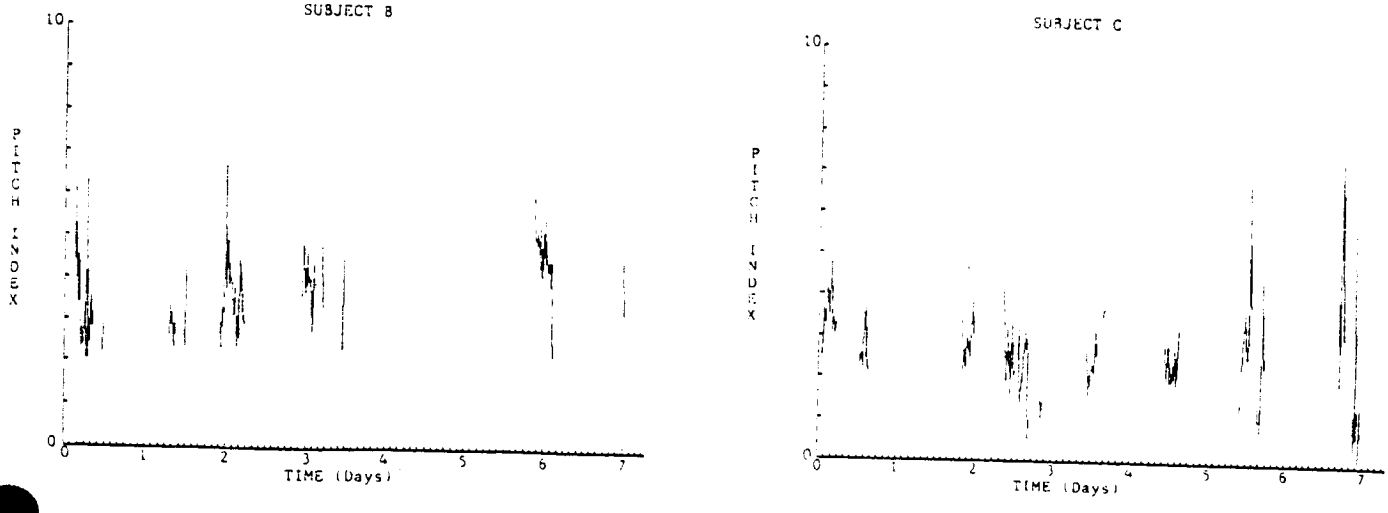

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Figure 12. Visual Orientation Illusion: When an observer views another person floating with feet towards the Spacelab ceiling while himself in a similar orientation, the observer may suddenly feel that the true floor has subjectively become a "ceiling", and so no longer feels "upside down".

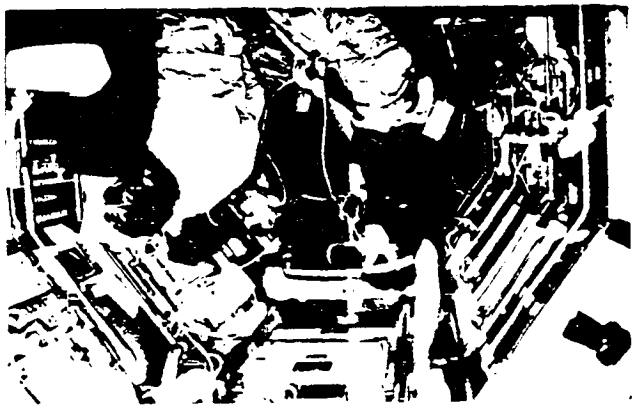

Figure 13. Visual Reorientation Episode: The visual orientation illusion of Figure 12 typically reverses when the people in view reassume a "normal", feet towards the true floor orientation. Observer then experiences a visual reorientation episode, and suddenly feels "upside down".

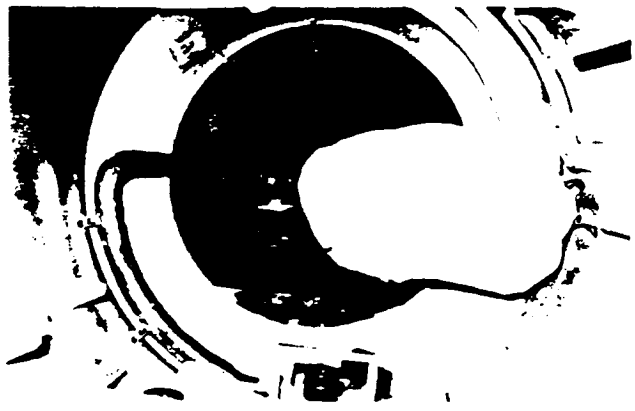

Figure 14. Interior view looking forward of the tunnel connecting Spacelab with the Shuttle Orbiter mid-deck airlock. Travel through the tunnel could be disorienting.

experienced increased symptoms later that day (Graybiel, et al 1977). The lack of apparent correlation between drug use and sickness incidence may be because astronaut head movements have not been controlled or measured. Hence, even if drug use raised the sickness threshold (Reason and Brand, 1970), astronauts could then simply make a somewhat greater number of head movements before reaching their sickness threshold (Oman, 1982b). Unfortunately, on most missions, drug use is not always systematically recorded. Also, subjects are aware of exactly which drugs are being taken and why, so placebo effect is a potential problem in interpretation.

A second reason for the controversy surrounding space sickness has been the practical difficulty of studying the phenomenon in orbit. On Skylab, a pioneering attempt at testing with provocative head movements was made. However, controlled experiments did not begin until the fifth day of the flight, and by then most crewmen were apparently virtually asymptomatic to both the environment and the test stimulus used (Graybiel, et al, 1977). On other missions, basic information on the symptoms and adequate stimuli has been difficult to collect systematically. Most crewmen have had little formal training as observers, debriefing reports are anecdotal and retrospective, details are generally not readily available in the open literature, putative stimuli such as head movements are uncontrolled on operational missions, and provocative testing is usually discouraged for operational reasons. Spacelab 1 provided an opportunity for trained observers to document space sickness symptoms and the relationships with putative stimulus factors in unusual detail.

METHODS:

(Begin small print here)

Subjects were the 4 SL-1 science crewmembers, aged 35-53 at time of flight, and henceforth denoted as Subjects A-D. All were pilots, and one had flown in space

D5-52

Postural Responses Following Exposure to Weightlessness MIT/Canadian Vestibular Experiments on Spacelab 1: Part V

19P

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Key words: Weightlessness, Adaptation, Posture, Spaceflight, Electromyography
Running Title: Posture Following Weightlessness

SUMMARY

The four science crewmembers of Spacelab-1 were tested for postural control before and after a 10 day mission in weightlessness. Previous reports have shown changes in astronaut postural behavior following a return to earth's 1-g field. This study was designed to identify changes in EMG latency and amplitudes that might explain the instabilities observed postflight. Erect posture was tested by having the subject stand on a pneumatically driven posture platform which pitched rapidly and unexpectedly about the ankles causing dorsi- and plantarflexion. Electromyographic (EMG) activity from the tibialis anterior and the gastrocnemius-soleus muscles was measured during eyes open and eyes closed trials. The early (pre 500ms) EMG response characteristics (latency, amplitude) in response to a disturbance in the posture of the subject were apparently unchanged by the 10 days of weightlessness. However, the late (post 500 ms) response showed higher amplitudes than was found preflight. General postural control was quantitatively measured pre and postflight by a "sharpened Romberg Rails test". This test showed decrements in standing stability with eyes closed for several days postflight.

INTRODUCTION

Exposure to prolonged weightlessness produces postural changes both while weightless (Clement et al., 1984, 1985) and for several days postflight. Astronauts display a variety of postural difficulties upon returning to earth (Homick and Reschke, 1977, Homick et al., 1977). Subjects are unable to maintain stable posture with eyes closed, make wide turns around corners, use a wide stance to stand and walk, feel sensations of lateral acceleration while walking, are unable to detect small changes in head position, and experience vertigo during rapid head motions. In the absence of visual cues, quasistatic orientation with respect to the vertical and postural stability is normally based primarily on cues from the otolith organs (particularly from the utricular macula for the head erect position). Dynamic postural stabilization (especially damping) is enabled by signals from the vertical semicircular canals (Flourens, 1824). Explanations for the postflight postural instabilities may lie in the changes in central processing of vestibular information that take place with long and continuous exposure to weightlessness. The effects of weightlessness on the vestibular system are not well known. Changes in postural stability may be the result of changes in any of several postural control system components.

The experiments described here were performed to document the postural responses which occur during postflight re-adaptation and to test hypotheses which might explain the postflight instability. Instabilities caused by delays in the EMG response to platform tilt might be reflected in latency to postural disturbances. EMG amplitudes from the muscles that control stability of the subject following a change in support surface might be altered and further destabilize the subject. Finally, delayed or sluggish

long loop reactions might be reflected as changes in the characteristics of the late response, especially with eyes closed. Two postural programs were conducted - a tilting posture platform test and a modified sharpened Romberg test.

METHODS

The four SL-1 payload crewmembers were tested pre and postflight in the Baseline Data Collection Facility, as specified by Young et al., (1986a). It was possible to test only subjects A and B within 6 hours after landing.

Posture Platform: Changes in standing posture were initiated by a pneumatically driven platform. It imparted a tilt up or down disturbance of 5° in 15ms (Crites, 1976). The raw EMG signals from the ankle flexors and extensors were recorded. Each EMG channel had a fixed gain (1000) amplifier followed by a bandpass filter (20 - 1000 Hz) a full-wave rectifier and finally a 10 Hz low pass filter. The two EMG signals were sampled for 10 seconds at 200 samples per second per channel by a microcomputer that also controlled the movement of the platform. If a baseline shift or other event interfered with the trial, the experimenter could stop and repeat the trial discarding the old data.

Prior to testing, the skin over the tibialis anterior (TA) and the gastrocnemius-soleus (G-S) muscles of the left leg was cleansed with alcohol and scratched with a needle at the point where two surface EMG electrodes (HP 14445A pre-jelled disposable Ag-AgCl) were placed over each muscle group (6-8cm apart); an indifferent electrode was placed on the front of the leg over the tibia 12 cm down from the patella. Tattoos on the skin over the medial head of gastrocnemius muscle served as landmarks so that electrode

placement would be consistent from one test session to the next. TA electrodes were positioned 10cm below the bottom of the knee.

Subjects were tested under eyes open and eyes closed conditions. Initially, six trials were performed consisting of a randomized set of three up and three down tilts of the platform with eyes open, followed by a different randomized set of six trials with eyes closed. The random presentation of the platform motion was designed to reduce predictive effects that can alter postural responses. The support surface was tilted to increase the difficulty of the posture control task. As the platform is suddenly tilted proprioceptive reflexes that normally stabilize posture are inappropriate to maintain stability. This necessitates the use of other sensory systems, including vestibular, to compensate for the disturbance in posture (Nashner et al., 1982; Diener et al. 1983). Finally, eyes closed testing removes the important visual information used in low frequency stabilization of the body.[1]

Subjects wore hard soled shoes and were instructed to stand on the platform with their eyes open (or closed) facing a white wall (1 meter away), head erect and legs straight but knees not locked. During eyes open trials, the subject was also instructed to "look straight ahead". The experiment room had many visual cues to the vertical but they were in the far periphery of the subject's field of view when the eyes were directed straight ahead. The initiation of a trial was delayed for a random length of time (3 to 6 sec) to reduce the predictability of the stimulus. At the

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[1] The choices of our tests were constrained by available experiment time and the postural techniques available at the time the experiment was designed. Consequently, more recent or time consuming techniques that might have more directly addressed some of the postural issues could not be used.

end of each experiment, four EMG calibration trials were run. These consisted of the subject making maximum dorsi- or plantarflexion movements by pointing the toe up or down in alternating trials. The entire experiment took 20 minutes to perform.

The "Sharpened Romberg" test refers to a standardized procedure for measuring standing stability (Graybiel and Fregly, 1965). This test has been used to study posture in space crews (Homick et al., 1977) and labyrinthine deficient patients (Graybiel and Fregly, 1965). Results can thus be compared to other results from crews from longer duration flights both past and future. Equipment for the "rails" experiment consisted of a 1/2" x 3/4" x 8' (H x W x L) narrow rail mounted on a 2" x 4" x 8' piece of lumber and a 1/2" x 2 3/4" x 12" wide rail of aluminum stock (Homick and Reschke, 1977).

Narrow rail walking: The subject walked arms folded in front of him, heel to toe, along the narrow rail. (Six steps maximum)

Narrow rail standing: The subject stood, eyes open, with arms folded, in the heel to toe position on the narrow rail for a maximum of 60 seconds per trial.

Wide rail standing/eyes closed: The subject stood heel to toe on the wide rail and when stable, closed his eyes. The position was maintained for a maximum of 60 seconds.

Wide rail standing/eyes open: The subject stood heel to toe on the wide rail for a maximum of 60 seconds, eyes open.

All trials were terminated if the subject unfolded his arms or placed a foot on the floor. Unlimited gyrations were allowed, if stable posture was regained. The operator measured the duration of the test or, in the case of

the narrow rails walking, the number of steps. Individual scores for each subject were the sum of the best three out of five trials for that test. In each test, the maximum score possible was computed as the sum of three perfect scores.

Analysis: The EMG data from each subject was analyzed for latency, area from the beginning of the initial EMG response to its peak, and frequency of oscillation of the late, post 500ms, response. Latency was measured from the platform tilt command to the start of the first EMG response, defined as a change in baseline level which exceeded the noise level by a factor of three. A peak was identified as the largest EMG amplitude (arbitrary units) that occurred within the first 500 ms after the tilt command. While this worked well with a majority of the data, some activity was so small that some judgment was necessary to identify the peak in the response. This mainly occurred for TA activity in the tilt down trials. With a sample rate of 200 per sec, a precision of 10ms was achievable. The strength of the EMG activity from the TA and G-S muscles was estimated for the initial response after the onset of the disturbance by integrating over the interval from the beginning of the initial EMG response to its peak. This single value was in proportion to the filtered EMG activity of that muscle. These response area values were scaled appropriately within each subject by using the EMG calibration data for that day's experiment session to compensate for changes in recording sensitivity from one day to the next. Session to session variation in EMG amplitude were examined. The oscillations in the EMG activity following the initial response were measured as the time interval between the peaks in the

filtered response. Observations of whole body posture were based on video recordings of subject posture made during the test.

RESULTS

EMG activity of Subject B during the first tilt up trials with eyes open and closed on test days L-10, R+0 (6hrs after landing),R+1 and R+6 is shown in Figure 1. We chose to use the last test preflight, L-10, since it represented the state of the subject's posture control closest to launch. We also felt that, due to the variability of the responses, a better understanding of the relationship between pre and postflight EMG activity would be possible by examining individual responses rather than averaged data which might obscure some of the fine details in the response. The tilt up trials produced the most unstable condition for the subjects during both pre- and postflight testing as they do for the normal population. The restricted dorsiflexion range of the foot caused the transfer of much of the platform tilt up momentum to the torso rather than allowing it to be absorbed by the ankle as is the case for the tilt down motion.

The eyes open (EO) tilt up responses of the TA muscle show small changes between the responses on the last preflight test, L-10, (Figure 1a) and postflight R+6 (Figure 1c). On R+0 (Figure 1b) and R+1 (Figure 1d), the first response to a tilt up has a larger initial response. However, we could not find any consistent pattern of change in the initial response amplitudes within or across subjects. Often a large initial response would return to the level seen preflight on the following tilt up responses. This response does not appear to be related to readaptation to 1g since others have reported similar changes in laboratory subjects' response to successive

postural disturbances (Wicke and Oman, 1982; Nashner, 1976; Nashner et al., 1982). No similar changes were observed in the initial G-S response. The late responses have generally the same shape, being characterized by one or two peaks following the initial peak at with most of the response remaining flat for the rest of the period.

The eyes closed (EC) tilt up trials qualitatively showed postflight changes primarily in the late response. The initial peak changed very little if at all from the preflight level. The late response on R+0 (Figure 1b) and R+1 (Figure 1d) shows several large and prolonged periods of EMG activity in the TA and G-S muscles as the subject fought to maintain balance. These contractions sometimes continued throughout the trial period. Although patterns of oscillations in the muscles were also recorded preflight, the consistency and the amplitude of the postflight oscillations on R+0 and R+1 were greater than those found subsequently or preflight. The EMG activity on R+1 (Figure 1d) is consistent with the observation of the authors and the comments from subject B after the test, that he was still unstable on R+1 despite his comments prior to the testing that normal stability had returned. Successive eyes closed tilt up responses from subject A on L-10 (Figure 2a), R+0 (Figure 2b) and R+1 (Figure 2c) show clear changes between preflight and R+0 data with less distinction on R+1. The increased amplitudes throughout the recording session clearly separated preflight from R+0 EMG responses in both subjects A and B. By R+4 the crew responses were not different from those preflight and were similar to those seen for R+6 in Figure 1c (subject A).

The tilt down trial responses (not displayed) changed from pre to postflight. The eyes open (EO) and eyes closed (EC) responses on preflight

L-10 and postflight R+6 showed a similar pattern of TA and G-S activity. The postflight data on R+0 and R+1 showed higher TA activity than that found preflight or on R+6. However, this increase in TA activity which would be inappropriate to stabilize the tilt forward of the subject produced by the platform movement, was not strong enough to cause problems since subjects were more stable during tilt down trials than tilt up both pre and postflight.

LATENCY

Tilt up trials: Despite the destabilizing nature of the tilt-up trials, preflight and postflight latencies for the TA muscle were apparently unchanged within each subject. The data in Figure 3a is representative of our subject population and shows the latencies for pre and postflight tests on subject B who was tested on R+0. Several aspects are notable regarding the pre- and postflight data. Firstly, the variability of the latency is less postflight than was found preflight for both the TA and G-S muscles for the tilt-up tests. Secondly, the TA latencies were consistently longer than the G-S latencies ($p < .001$) postflight but not preflight. Finally, there was no significant difference in eyes open and eyes closed latencies pre or postflight. These results were consistent across subjects.

The large spread of latencies preflight may have resulted from our indiscriminate lumping of all TA and all G-S latencies for each experiment. However, when we subtracted the latency between corresponding TA and G-S responses for each trial, pre and postflight relationships were similar to those shown in Figure 3.

Tilt down trials: The tilt down data was absent of any clear separation between postflight TA and G-S latencies as found above for all

subjects. As the data in Figure 3b show, the latencies from each muscle group are intermingled in both the pre and postflight trials for each subject. Similarly, the eyes open and eyes closed data showed no significant difference either within the preflight or postflight data or between preflight and postflight data. Taking the differences between TA and G-S muscle latencies did not show any additional relationships in timing of these contractions.

AMPLITUDES

Tilt up trials: The integrated EMG values plotted in Figure 4a show a high degree of variability. The relationship between TA and G-S amplitude values were not uniform within subjects. The compensated amplitude (see Analysis) of the early response did not show any clear change preflight versus postflight in any subject. Even for the two subjects who were tested on R+0 (one of which is displayed), there was no demonstrable difference within responses pre and postflight. The eyes open and closed trials produced similar amplitude values in each subject for pre and postflight testing. We could find no significant difference between preflight and postflight amplitude values either eyes open or eyes closed.

Tilt down: The TA and G-S amplitudes for the tilt down trials showed no significant difference across pre or postflight testing nor between data from eyes open and eyes closed trials. Figure 4b is a representative display of the amplitude data from our other subjects. In general, the amplitude of the initial G-S response was smaller and more variable when it acted as the agonist (tilt-down) than the TA muscle response when it acted as the agonist (tilt-up).

To insure that method of compensating the EMG amplitude values did not obscure some relationship across test days pre- and postflight, we examined uncompensated data for our subjects as well as the calibration values used on each day's data. The calibration values showed no trends or significant changes between preflight and the first 4 days postflight. No additional relationships were revealed in the uncompensated data in our subjects.

LATE RESPONSE CHARACTERISTICS

In both the pre and postflight testing, the tilt up trials produced a measurable late response mainly in the form of oscillation of the EMG activity in the TA muscle. Consequently, we chose to analyze the late component of the posture response by examining the period and number of EMG oscillations that occurred from the end of the first EMG peak to the end of the data record. The peaks were determined as the midway point between the rising and falling slopes of the responses. The durations were measured for each set of trials (eyes open, eyes closed) for each day tested preflight and postflight. The resulting data from each day was separated into eyes open and eyes closed and displayed in histogram form in Figure 5 for subject B. The eyes open preflight responses show a broad range of durations with only a few observations in each bin. On postflight days R+0 and R+1 this broad range has narrowed and is shifted slightly to shorter durations. The return to the preflight characteristics can be seen at R+2, R+4 and R+6. Comparison of eyes open (EO) and eyes closed (EC) data postflight shows that the number of oscillations is increased with eyes closed over the same band of durations. Comparing preflight EO data to postflight EO data shows little change. However, postflight EC data shows the appearance of oscillations with shorter durations compared to preflight. For subjects A,

C and D (not shown), the range of responses and the number of observations is about the same as found for subject B, but the shift towards shorter durations was less noticeable.

General Observations

R+0. The two subjects tested 6 hours after landing showed several postural changes from their preflight test sessions. Subjects were less stable, showing for the first time loss of balance on the eyes closed tilt up trials. Tilt down and eyes open tilt up trials were better tolerated with no dramatic loss of stability. Subjects showed larger sway related EMG activity when stabilizing posture after tilts postflight. Subjects used a wider stance to stand during preparation for testing. They used aids to stand on one foot during calibrations, tried to limit head movements, used a crouched posture to stand and commented that head motions seemed exaggerated. During the testing session, subjects were first unstable (mainly to tilt up trials) but by the end of the session (20 min) showed an increased ability to maintain posture during the tilts. Also, the consequences of fluid redistribution after returning to 1-g caused subject B to request a 5 minute break in testing, after which he completed the tests without incident.

Prior to posture platform testing, Oman (SL-1 co-investigator) had subjects A and B make deep knee-bends[2]. Only subject B reported an illusory motion of the floor. Subjectively, the floor appeared to come up to meet him. This subject estimated that one-third of the bending of the legs was due to apparent movement of the floor and not to the active movement on his

[2] In addition, subject B reported oscillopsia to pitch, roll and yaw head movements. Subject A reported no oscillopsia during similar head movements.

part. The illusion was strongest with eyes open but was also present with eyes closed. Tested three hours later, the illusion was still present eyes open, but was absent when tested on R+1. A similar illusion was experienced by all subjects during the 1.7g pullout phase of KC-135 parabolic flights conducted on R+4 and one year later.

R+1. Testing revealed that subjects were still unstable this day. On the initial tilt up trials, subjects B and D lost their balance but not to the extent experienced on R+0 for subject B. This instability was a surprise to the subjects who commented prior to the tests that their posture control had returned to normal and that they were not in any danger of losing their balance. This instability was reduced substantially on the following tilt up trial and continued to decline as the tests proceeded.

R+2 No subjects lost their balance on trials during these tests and comments from the crew indicated that they felt they were almost returned to preflight stability. By R+4, the subjects showed no problems dealing with the disturbances created by the platform motion. The same was true on R+6.

Quantitative measurement of whole body posture from the video tapes was not possible. However, reviewing pre and post flight video tapes did reveal several changes in posture strategy to handle the tilt disturbance. The differences postflight (R+0) compared to preflight were that subjects A and B used more of their body to absorb the tilt disturbance. This took the form of more hip motion postflight in an effort to minimize the motion of the head. However, we observed no change in hip motion after this disturbance, during the late response portion of the record. The static posture on 3 of the 4 subjects was not observed to be radically different while standing steady on the platform. However, Subject C showed a change

in platform posture preferring to assume a posture with knees and hip slightly flexed in his first test postflight on R+1. This subject commented that this posture felt more stable and comfortable.

The modified Sharpened Romberg results for each test and each subject are summarized in Table 1. In general, Subject A showed more postural stability and Subject D less stability than the age-adjusted population norms. For all the results, statistical significance was assessed by a paired t-test comparing each subject's average preflight score to the first two postflight tests on days R+0 and R+1 for A and R+1 and R+2 for B, C, and D.

DISCUSSION

The post flight instability in the absence of vision found on the Skylab crew (Homick and Reschke, 1977) was again dramatically present on the Spacelab-1 crew after landing, and continued through at least R+2. The subjective feeling of dependence on visual cues to prevent falling, and wide stance in walking, were borne out by the quantitative ataxia tests (rails test). Subject O.G., who reported surprise at his instability, related a confirming incident that occurred on the night of R+0 and was similar to his experience after his 54 day Skylab mission. Having turned off the bedroom lights at the wall switch, he realized that he was unable to make his way to bed in the dark, and had to ask his wife to turn off the light once he had gotten safely to bed. This same subject said after falling off the wide rails with eyes closed on R+2 "at least now I can tell when I'm falling", and indicated that prior days he was "unlikely to detect an incipient fall in time to prevent it". The relatively greater attention paid to visual cues in spatial orientation postflight, found in the visual-vestibular

interaction experiments (Young et al., 1986b), was also borne out by the lesser decrement in the eyes open postural performance found in the rails and tilt platform tests. These findings are supported by the postflight stability results of Reschke et al. (1985) on another posture test and with the posture platform.

Despite the observed instabilities of erect posture, we found that there was no change in the early EMG latency or amplitude responses from our subjects. The small number of observations per test and the large variability of the data makes us cautious about over-interpreting these data. However, these results indicate that weightlessness for 10 days does not change the early postural control patterns as measured by EMG latency and amplitude following a disturbance in posture. Due to the multi-sensory nature of the postural control system, deficits in any one system (e.g., the vestibular system) may be masked or compensated by other systems involved in posture control. For example, while studying patients with vestibular impairments, Nashner et al., (1982) found using forward and backward movements of the support surface, that EMG latencies changed only in the most severely impaired patients and then only during eyes closed testing. This showed that congruent support surface inputs were sufficient to maintain posture control in all but the most severely impaired patients and only with eyes closed. The systems that contribute to the early postural response include the simple ankle stretch reflex (which is destabilizing for our disturbance) as well as vestibular connections to the spinal reflex arc. Although our tests did not allow differentiation between proprioceptive or vestibular mediated instability, changes in spinal activation seem unlikely in the light of Reschke's et al. (1984) result (postflight) showing

increased spinal activation only during free-fall. In addition, Watt and Money (1986) showed that the early otolith-spinal response to falls measured by EMG was at preflight levels at the time of testing postflight despite the reduction found inflight. However, the posture disturbance used in our tests activated both otolith and semicircular canal responses. The results from tests of semicircular canal function from previous flights (Graybiel et al., 1977) and pre and postflight in these crewmembers, have shown no change in the VOR gain (Benson et al., 1985) and preliminary results indicate no change in phase (Oman, in preparation). Our results and those of others indicate that early postural responses to disturbances in postural equilibrium are not changed from preflight levels when tested 6 hours postflight. However, any change which was abolished during the first 5 hours after landing (earliest test reported here was 6 hours postflight) would not have been observed. Indeed all four crew members said that they had considerable difficulty standing in the shuttle immediately after landing, and some commented that they had to practice walking around the flight deck to avoid the embarrassment of falling down the stairs. Clearly, earlier post landing tests will be required. In addition, postural tests which can independently control conflicting sensory information from proprioceptive, visual, and vestibular inputs (Nashner et al., 1982) are needed to address questions of postural control that our limited tests could not answer. For example, questions remain regarding changes in the hierarchical nature of the postural control, or whether changes in posture were results of sensory adaptations or from more fundamental changes in CNS function in the brainstem.

The observed postural instability in the absence of any provable early EMG change following the disturbance stimulus may indicate that muscle atrophy, known to be associated with exposure to weightlessness (Thornton and Rummel, 1977; Whittle et al., 1977), might contribute to this condition because control signals at preflight levels may be inadequate to control posture with partially weakened muscles. Crew members did show a loss of body weight and muscle wasting was observed but not measured. Nevertheless, there are several logical arguments against this mechanism as a major contributor to postflight instabilities. First, the postflight postural instability is strongest with eyes closed. One might expect to find that both eyes open and eyes closed conditions might be equally affected by muscle wasting. Secondly, if the eyes open condition did provide more stability for some reason, one would expect there to be a larger early EMG response with eyes open than with eyes closed (presumably to increase the force generated by the weakened muscle); both eyes open and eyes closed conditions showed no difference in pre and postflight EMG early response amplitude values. In addition, larger late EMG responses were found in eyes closed conditions postflight. Consequently, we believe that any muscle atrophy that occurred in the crewmember's postural muscles on this mission did not play a major role in postural instability induced by inadequate early EMG response magnitudes used to stabilize posture in our subjects.

The absence of any significant change in the period of the EMG oscillations measured for the late response argues against an increase in the vestibular dead zone being responsible for the increase in sway postflight eyes closed. Such an increase would be expected to lengthen the time to detect an off vertical position of the head/body since the sensors

would need larger off vertical head and body movements in order to detect this change. One might also expect to find the period of the EMG oscillations would correspondingly increase. However, the oscillation periods postflight remained within the same range of periods as preflight and tended to be somewhat shorter on R+0 than those found preflight, the opposite we would have predicted with such a deficit. However, our stimulus was limited in its ability to induce consistent vestibular stimulation. Disturbances at the ankles needed to travel through several body segments prior to reaching the head. This usually results in somewhat uneven perturbations of the vestibular system. Consequently, future tests should attempt to control head movement or measure head motions during the tests. This would allow direct assessment of vestibular input to the postural control system.

Despite the small changes in duration of the late response, the amplitudes of these responses were observed to be larger early postflight than preflight or on R+4 and R+6. These long-loop postural control responses are believed based on vestibular inputs and the perception of body position from proprioceptive and voluntary mechanisms. Nashner et al., (1982) have proposed a hierarchical concept by which vestibular inputs are used to gate the use of sensory information for posture control. According to this hypothesis, conflicting sensory information is referenced to signals from the vestibular system. Control of posture is mediated by that sensor which conforms to vestibular inputs. However, should the vestibular system still function but the interpretation of the incoming signals be changed, this might cause systems to focus on inappropriate sensory information to

control posture. Alternatively, an unreliable vestibular system might cause the introduction of a new reference system. The increase in the late EMG response amplitude suggests that an altered estimation of body position from the vestibular or proprioceptive systems takes place immediately postflight. However, whether this is due to a change in hierarchial control by central nervous system centers or to a change in postural strategy from control about the ankles to control about the hip, is beyond the scope of our data. Although one could presume a change in hierarchial structures to meet the required sensory rearrangement or alteration in control around the hip versus ankle, more expansive tests measuring body segment motion will be needed to substantiate such speculations.

The illusion experienced by subject B of the floor coming up to meet him while he made deep knee bends on R+0 prior to platform testing may hint at an alteration of vestibular interactions with visual and proprioceptive information during vertical accelerations. We speculate that the association between the vestibular sense of vertical accelerations and visual or proprioceptive (leg musculature) information is different immediately postflight than it was preflight. An underestimation of vertical acceleration sensed by the vestibular system coupled with veridical information from visual or proprioceptive systems could set up sensory conditions that leads to the illusion that the supporting surface is moving. Considering that this subject was exposed to 10 days of weightlessness it is conceivable that the adaptation of the saccular otoliths to weightlessness may play some part in this illusion. Inflight, the absence of a constant 1g force may have in some manner changed the interpretation of vertical acceleration by the human from what it was preflight. Returning to earth

and the reimposition of the 1g force may cause the adapted individual to underestimate the magnitude of acceleration. However, a similar illusion experienced during the 1.7g portion of parabolic flight has been explained by Lackner and Graybiel (1981) using proprioceptive mismatch between alpha and gamma motor signals. A clearer understanding of the mechanisms that are at work in the immediate postflight period awaits further study.

All of the above observations support the conclusion that there is a definite and long lasting effect of sustained weightlessness on higher level descending postural control pathways although no postflight modulation of the short latency ankle or otolith-spinal reflexes take place. Changes in postural strategy, as opposed to latency, support the findings of others. For example, Reschke et al., (1985) using a related posture platform test with the same subjects, also found minimal effect on EMG latency, but a change in the hip/shoulder postural stabilization strategy. These observations, along with others, are consistent with a sensory-motor reinterpretation hypothesis as an explanation for postflight eyes closed instability (Young et al., 1984,1986a; Parker et al., 1985; Reschke et al., 1984).

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FIGURE LEGENDS

Figure 1. (a) Tibialis (TA) and Gastrocnemius-Soleus (G-S) EMG responses from Subject B during 5° tilt-up disturbances of the posture platform on launch -10 days (L-10), (b) Return plus 6 hrs (R+0), (c) Return plus 6 days (R+6), and (d) Return plus 1 day (R+1). The vertical line passing through the data represents the initiation of the platform tilt up. Eyes open (EO) and eyes closed (EC) responses are shown for each test day. The rectified and filtered EMG data in this figure were plotted with the same scale factor. Time markings as indicated apply to all plots. The zero baseline is indicated by a dash line on those traces where the response did not start at baseline.

Figure 2 TA muscle EMG responses from subject A to three successive eyes closed tilt up motion of the platform on (a) L-10, (b) R+0 and (c) R+1. Numbers to the right of each response indicates precedence of responses on each test day. In each case the EMG level returns to zero at the initiation of the platform tilt-up. Time markings as indicated apply to all plots.

Figure 3. The latency from the command to tilt the platform 5° to the start of the EMG response for Subject B. (a) Tilt up and (b) tilt down. The preflight data is plotted on negative days (ie. -10) and the postflight data from 0 to 6. Closed symbols represent antagonist muscle data in this and all other such graphs.

Figure 4. EMG amplitude values for the initial response from subject B. The vertical scale is given in arbitrary units since it was intended for relative comparisons of the data. (a) tilt up and (b) tilt down.

Figure 5. Histogram plot of durations from the oscillations in the EMG activity of the late response for pre and postflight data in subject B. Eyes open (left) and eyes closed (right) data for TA data only. Vertical scale represents number of observations and bin widths are 100 ms wide.

TABLE 1 MODIFIED SHARPENED ROMBERG TEST

I. WALKING ON 3/4" RAIL (NUMBER OF STEPS, 18 MAXIMUM SCORE)

	L-180	L-152	L-120	L-65	L-44	L-10	AVERAGE PREFLIGHT	R+0	R+1	R+2	R+4	R+6	POPULATION AVERAGE AGE ADJUSTED
A	15	15	15	14	18	16	15.5±1.4	[12	12]**	13	17	15	9.2±4.0
B	18	13	15	18	18	18	16.6±2.2	-	16	18	18	18	12.5±2.6
C	18	18	18	18	18	17	18.0±0.4	-	17	15	18	16	12.5±2.6
D	15	14	11	9	12	13	12.3±2.1	-	10	11	10	11	12.5±2.6

II. STANDING ON 3/4"RAIL (NUMBER OF SECONDS, 180 MAXIMUM SCORE)

	L-180	L-152	L-120	L-65	L-44	L-10	AVERAGE PREFLIGHT	R+0	R+1	R+2	R+4	R+6	POPULATION AVERAGE AGE ADJUSTED
A	24	12	14	13	26	8	16.0±7.2	[12	9]*	18	10	12	13.2±5.9
B	24	26	31	18	17	18	22.3±5.6	-	[12	18]*	16	16	37.6±32.0
C	57	14	19	26	49	22	31.0±17.5	-	[19	15]**	18	15	37.6±32.0
D	19	8	11	11	13	9	11.8±3.9	-	[6	8]*	9	10	37.6±32.0

III. STANDING ON 2 1/4" RAIL EYES CLOSED (NUMBER OF SECONDS, 180 MAXIMUM SCORE)

	L-180	L-152	L-120	L-65	L-44	L-10	AVERAGE PREFLIGHT	R+0	R+1	R+2	R+4	R+6	POPULATION AVERAGE AGE ADJUSTED
A	178	77	66	101	126	83	105.0±41.0	[15	22]***	48	42	151	24.2±14.0
B	98	180	55	87	127	170	119.0±48.8	-	[18	43]***	145	116	103.8±58.37
C	111	71	23	95	106	170	96.0±48.5	-	[16	43]***	46	51	103.8±58.37
D	50	63	22	15	32	14	33.0±20.0	-	[9	17]**	20	19	103.8±58.37

IV. STANDING ON 2 1/4" RAIL EYES OPEN (NUMBER OF SECONDS, 180 MAXIMUM SCORE)

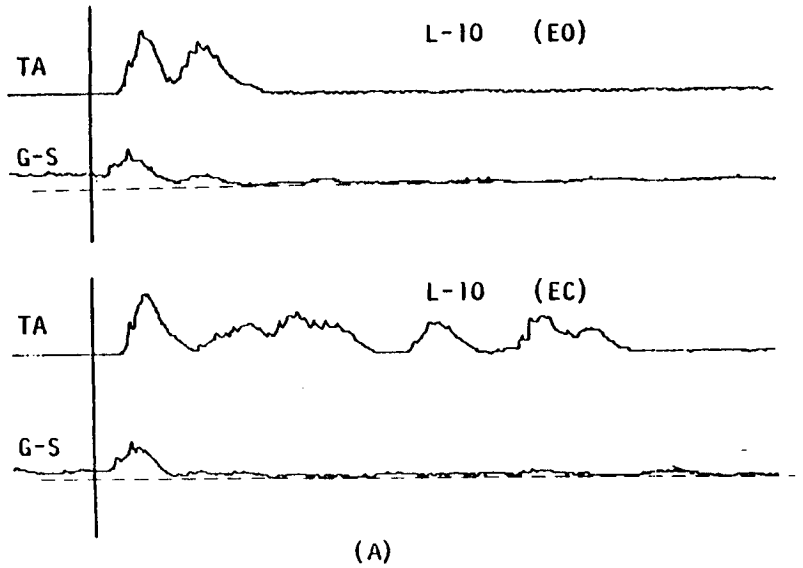
	L-180	L-152	L-120	L-65	L-44	L-10	AVERAGE PREFLIGHT	R+0	R+1	R+2	R+4	R+6
A	180	180	180	180	180	180	180.0±0.0	180	180	180	180	180	-
B	180	180	180	180	180	180	180.0±0.0	-	180	180	180	180	-
C	180	180	180	180	180	180	180.0±0.0	-	180	180	180	180	-
D	180	142	111	164	86	36	120.0±53.5	-	[80	66]***	99	76	-

SIGNIFICANCE LEVEL

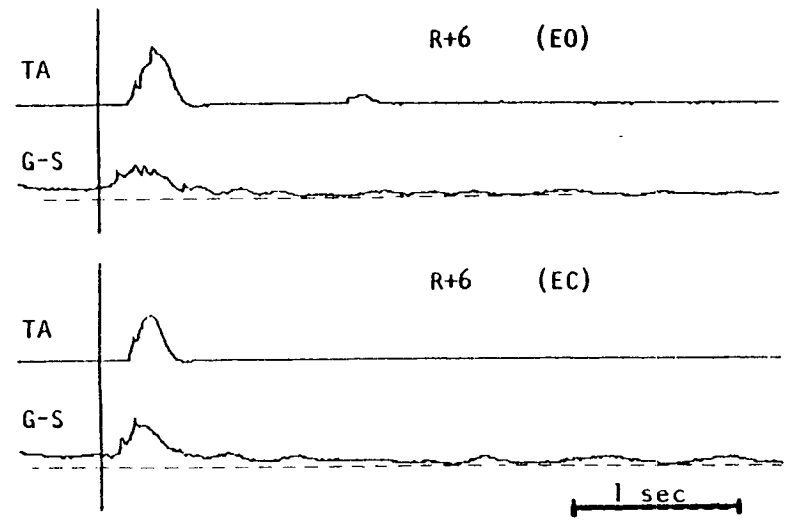
* $p < 0.05$

** $p < 0.01$

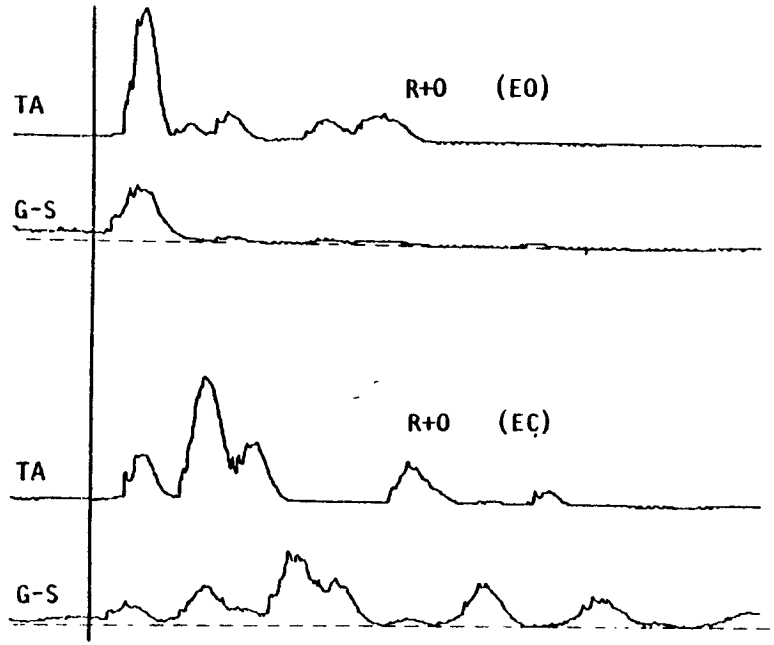
*** $p < 0.001$


L-10 (EO)
TA
G-S
L-10 (EC)
TA
G-S

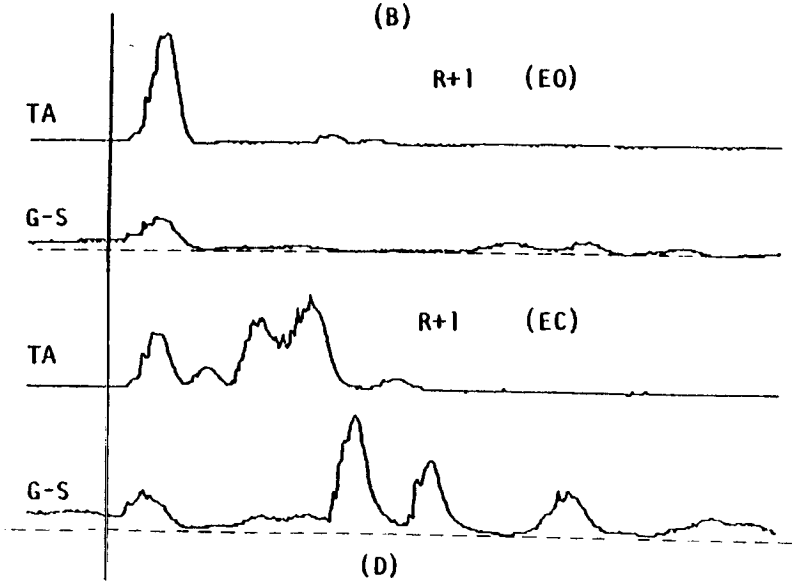
(A)


R+6 (EO)
TA
G-S
R+6 (EC)
TA
G-S
1 sec

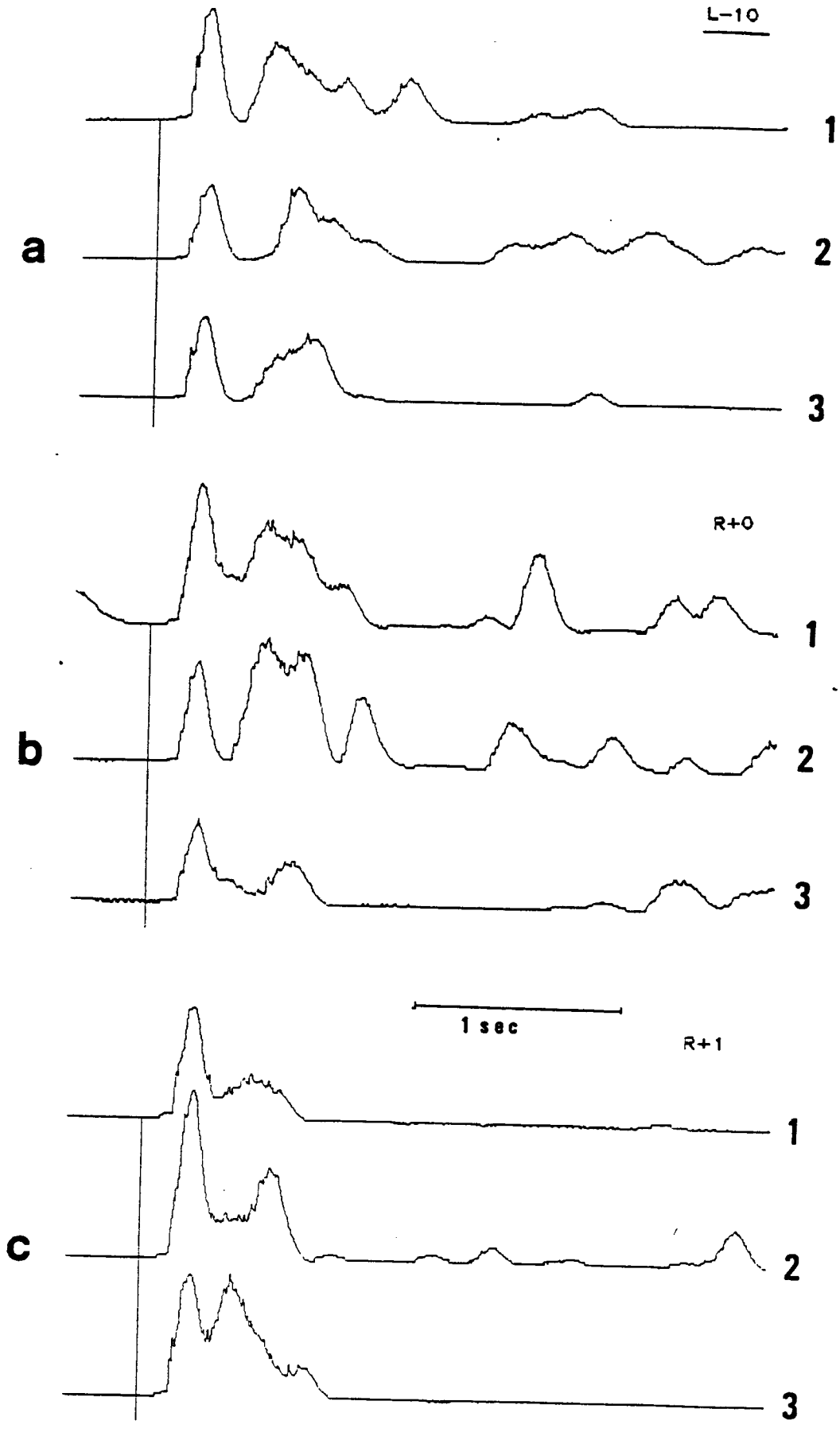
(C)

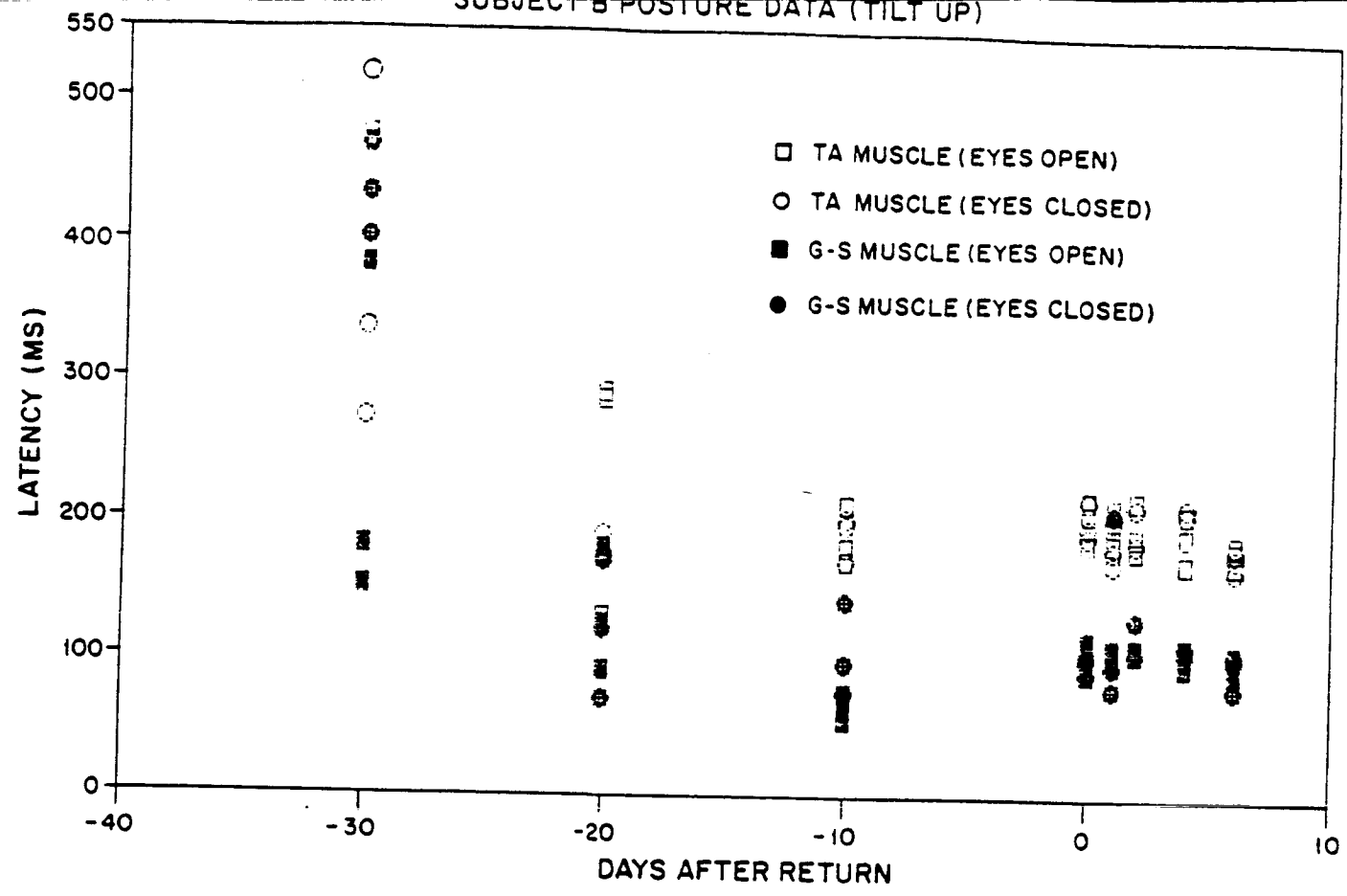

R+0 (EO)
TA
G-S
R+0 (EC)
TA
G-S

(B)

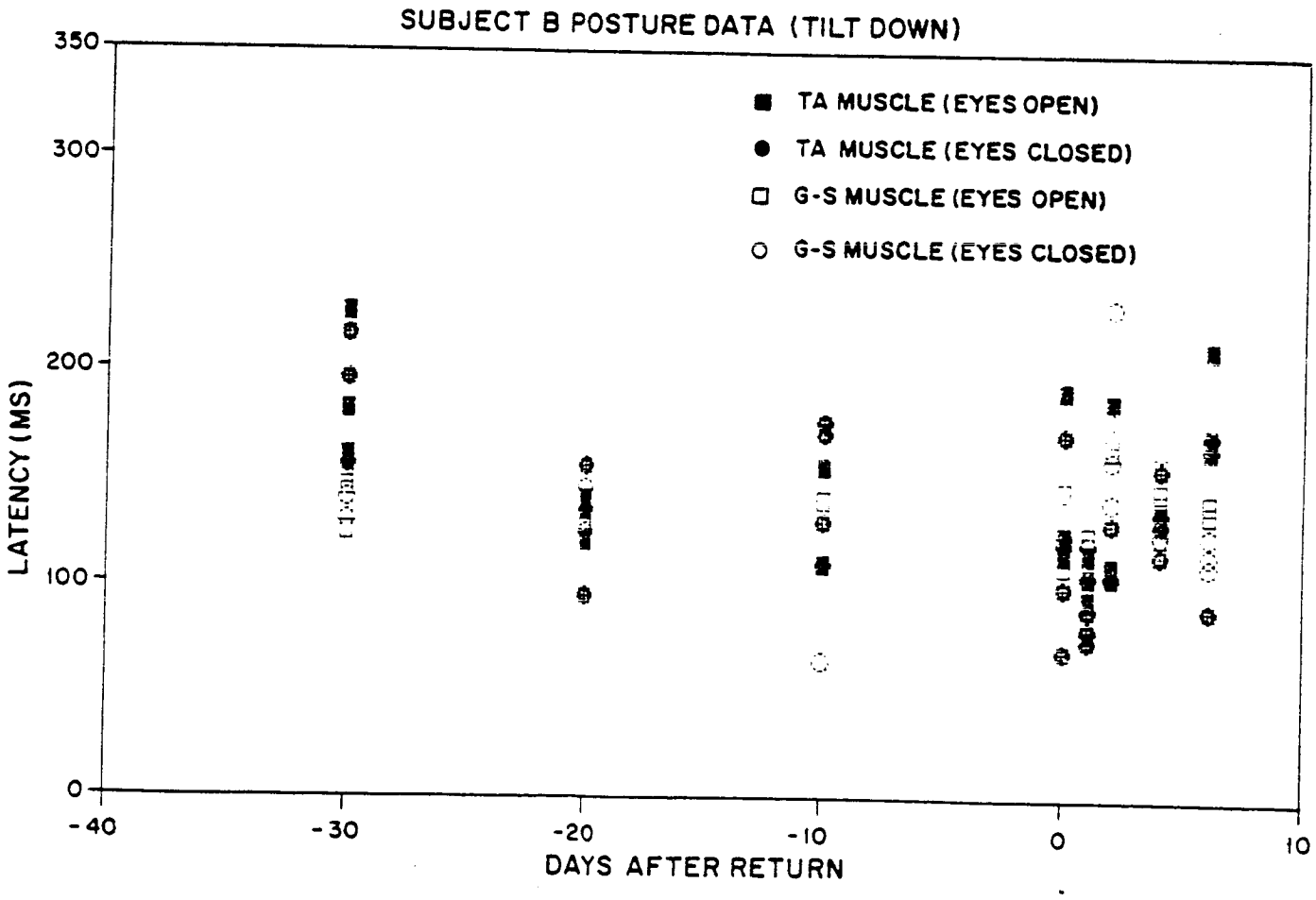

R+1 (EO)
TA
G-S
R+1 (EC)
TA
G-S

(D)

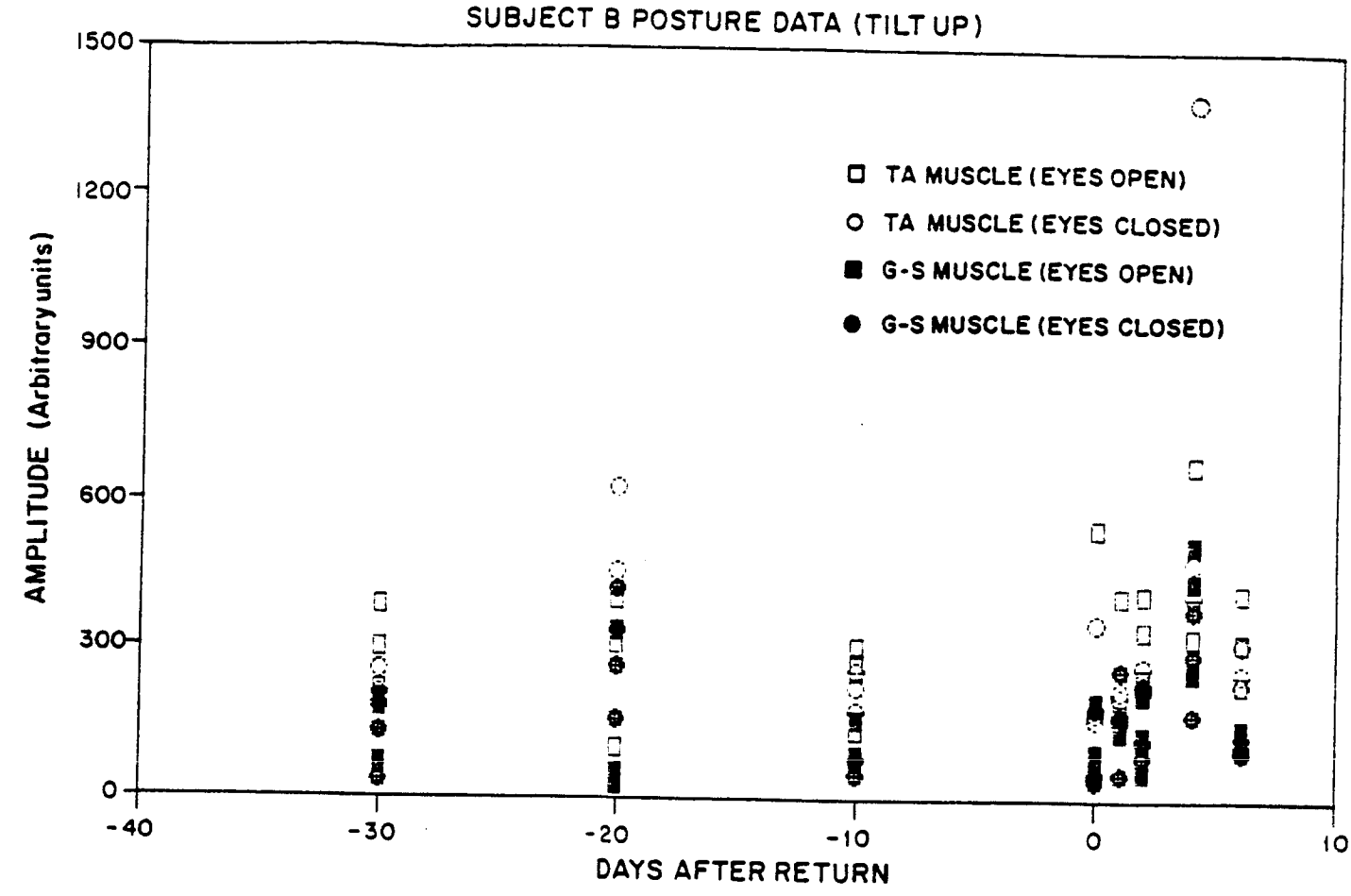

L-10
a
1
2
3
R+0
b
1
2
3
1 sec
R+1
c
1
2
3


SUBJECT B POSTURE DATA (TILT UP)
TA MUSCLE (EYES OPEN)
TA MUSCLE (EYES CLOSED)
G-S MUSCLE (EYES OPEN)
G-S MUSCLE (EYES CLOSED)
LATENCY (MS)
550
500
400
300
200
100
0
-40
-30
-20
-10
0
10
DAYS AFTER RETURN

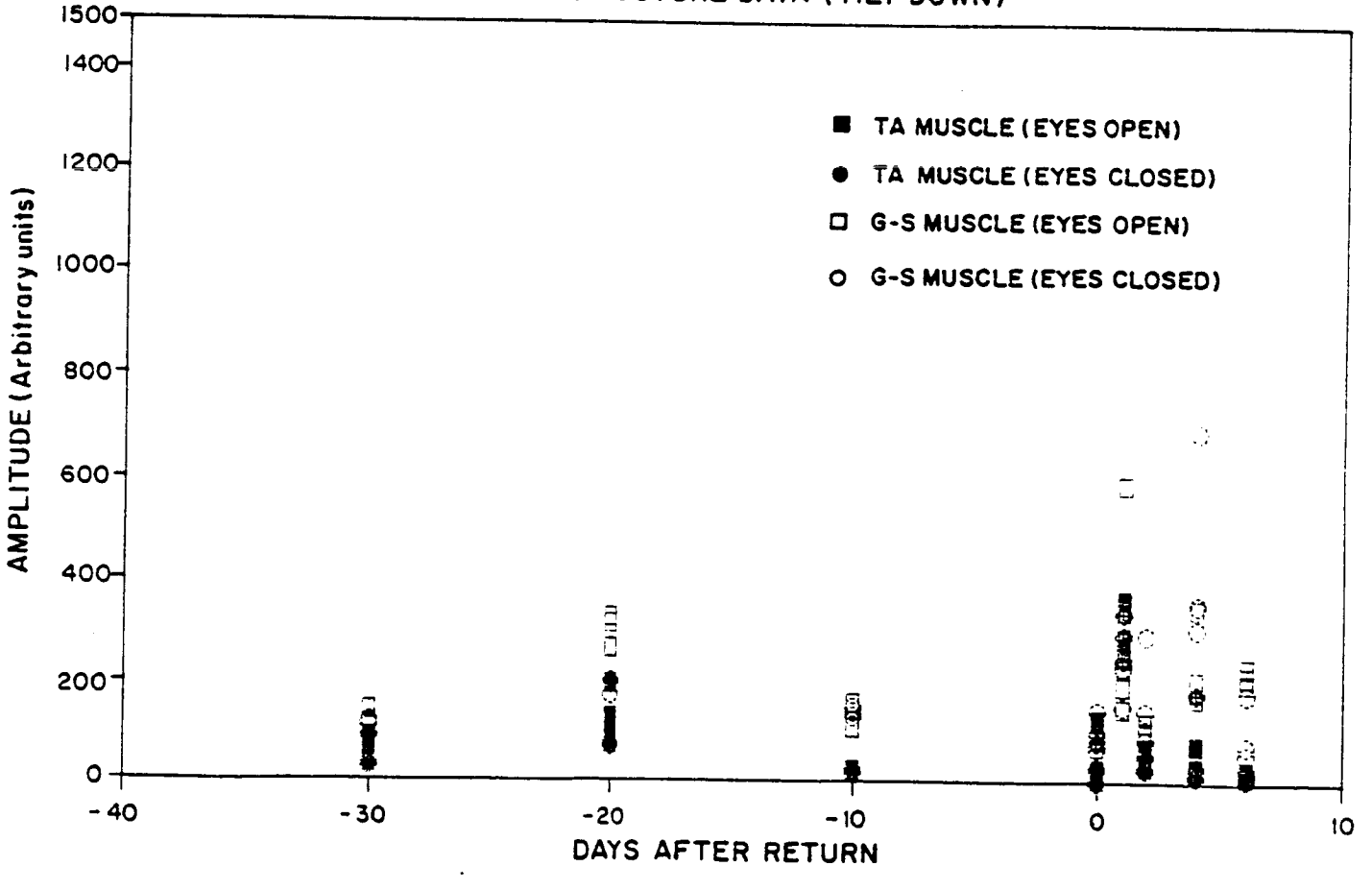
(a)


SUBJECT B POSTURE DATA (TILT DOWN)
TA MUSCLE (EYES OPEN)
TA MUSCLE (EYES CLOSED)
G-S MUSCLE (EYES OPEN)
G-S MUSCLE (EYES CLOSED)
LATENCY (MS)
350
300
200
100
0
-40
-30
-20
-10
0
10
DAYS AFTER RETURN

(b)

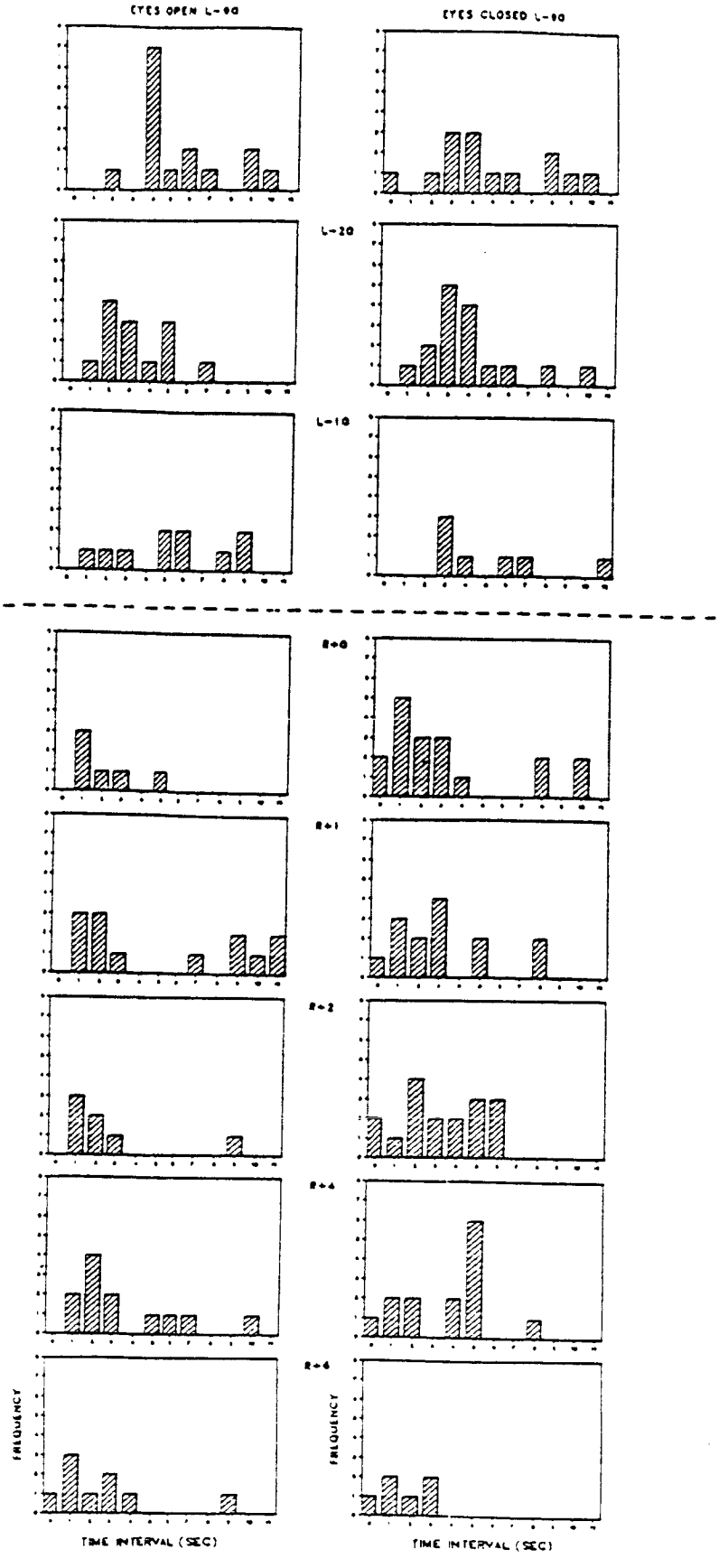

SUBJECT B POSTURE DATA (TILT UP)
AMPLITUDE (Arbitrary units)
1500
1200
900
600
300
0
-40
-30
-20
-10
0
10
DAYS AFTER RETURN
TA MUSCLE (EYES OPEN)
TA MUSCLE (EYES CLOSED)
G-S MUSCLE (EYES OPEN)
G-S MUSCLE (EYES CLOSED)

(a)


SUBJECT B POSTURE DATA (TILT DOWN)
AMPLITUDE (Arbitrary units)
1500
1400
1200
1000
800
600
400
200
0
-40
-30
-20
-10
0
10
DAYS AFTER RETURN
TA MUSCLE (EYES OPEN)
TA MUSCLE (EYES CLOSED)
G-S MUSCLE (EYES OPEN)
G-S MUSCLE (EYES CLOSED)

(b)

SUBJECT B


EYES OPEN L-90
EYES CLOSED L-90
L-20
L-10
R+0
R+1
R+2
R+4
R+6
FREQUENCY
TIME INTERVAL (SEC)
FREQUENCY
TIME INTERVAL (SEC)

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Vestibular Reactions to Lateral Acceleration Following Ten Days of Weightlessness

MIT/Canadian Vestibular Experiments on Spacelab-1: Part 6

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Key words: linear acceleration, ocular torsion, acceleration threshold, otoliths

SUMMARY

Tests of otolith function were performed preflight and postflight on the science crew of the first Spacelab Mission with a rail-mounted linear acceleration sled. Four tests were performed using horizontal lateral (y-axis) acceleration: perception of linear motion, a closed loop nulling task, dynamic ocular torsion, and lateral eye deviations.

The motion perception test measured the time to detect the onset and direction of near threshold accelerations. Postflight measures of threshold and velocity constant obtained during the days immediately following the mission showed no consistent pattern of change among the four crewmen compared to their preflight baseline other than an increased variability of response.

In the closed loop nulling task, crewmen controlled the motion of the sled and attempted to null a computer-generated random disturbance motion. When performed in the light, no difference in ability was noted between preflight and postflight. In the dark, however, two of the four crewmen exhibited somewhat enhanced performance postflight.

Dynamic ocular torsion was measured in response to sinusoidal lateral acceleration which produces a gravitoinertial stimulus equivalent to lateral head tilt without rotational movement of the head. Results available for two crewmen suggest a decreased amplitude of sinusoidal ocular torsion when measured on the day of landing (R + 0) and an increasing amplitude when measured during the week following the mission.

INTRODUCTION

Linear acceleration is a stimulus of prime importance in the investigation of the effects of weightlessness upon human orientation and balance. The absence of a constant 1 g bias on the graviceptors with the associated lack of any static gravitational tilt cues for different orientations in weightlessness confounds the normal role of the otolith organs. By periodically exposing a subject to transient linear acceleration, the state of adaptation of otolith and any other graviceptor responses can be assessed. Four tests using the U.S. Laboratory Sled were performed using lateral upright (y-axis) acceleration: perception of motion, closed loop otolith assessment test (CLOAT), dynamic ocular torsion, and horizontal eye deviations. Only the first three are discussed in this paper.

The experiments focussed on a range of human responses to linear acceleration, from the ocular torsion and linear eye deviation reflexes to judgement of perceived accelerations and the use of sensory information in a non-visual manual stabilization task. Inflight adaptation might alter any of these otolith dependent responses. To the extent that such adaptation carries over to postflight, it might be documented by postflight testing. The primary role of the otolith organs in each of the linear acceleration responses has been previously established. Patients lacking

otolith function have negligible ocular counterrolling in response to head tilt with respect to gravity (Miller, 1970) and are severely impaired in judging the vertical or in judging linear acceleration (Graybiel, 1974).

The reason for testing responses at the highest (0.83Hz) and lowest (0.42Hz) possible frequencies on the sled is to attempt to reveal any frequency selective otolith function adaptation. We suppose that inflight adaptation might reduce otolith function at low frequencies and increase it at high frequencies, where otolith cues of linear acceleration may continue to serve a useful function to the crew member traversing the cabin.

METHODS

Preflight/Postflight Testing: Postflight measurements were made during the period of readaptation following landing. In preflight/postflight testing, sufficient preflight measurements were made on separate occasions to establish a baseline for each test subject of some scalar (i.e. single-valued) response. The statistical characteristics (mean and variance) of the preflight responses were used in a Student T-test to determine whether the postflight response of a given test subject on a given postflight day significantly differs from the preflight responses at that time. In this way, any residual effects of adaptation to weightlessness could be assessed during the postflight period of readaptation to earth gravity. To the extent possible within operational constraints, postflight measures were taken under conditions as similar as possible to those used pre-flight so that each subject would serve as his own control. However, the experiment design did not distinguish between adaptation to weightlessness and any other change in the test subject (e.g. fatigue) as the cause of differences between preflight and postflight responses. Sled test sessions were conducted in the Baseline Data Collection Facility at the shuttle landing

site in California, 120, 64, 43, and 10 days before the ten-day Spacelab-1 Mission. Postflight testing sessions were conducted on landing day (R +0) three to five hours after landing for two of the crewman and on all of the 4 payload crew 1,2,4 and 6 days after landing.

Equipment: The US Laboratory Sled consisted of a chair and instrumented head restraint mounted on a cart which was guided along two cylindrical rails by four pillow blocks with recirculating ball bushings. It was patterned after a device at MIT used for Spacelab protocol development (Lichtenberg et al., 1982). A cable attached to both sides of the cart was wound around a pulley at one end and a winch drum at the other. The cable was held under 600 lbs of tension and the winch drum is driven by a 3.5 hp DC permanent magnet torque motor. The motor was controlled by a pulse-width modulated (PWM) velocity controller using tachometer feedback. Velocity commands to the PWM servo-controller were generated by a PDP 11/34 computer. The velocity commands followed mathematical trajectories which could be combined with a joystick signal under the control of the subject (see CLOAT, below). The sled was capable of controlled accelerations from 0.001 g to 0.7 g over an effective useable track length of 4.7 m.

The subject was restrained in a cushioned aluminum chair (ESA Space Sled Chair) by a five strap harness. The head was restrained within an instrumented foam-lined helmet. The helmet provided means for measuring acceleration at the subject's head, eye movement measurement by elecro-oculography (EOG), and attachment of a Nikon F3 camera to take pictures of both eyes. For tests requiring darkness, a shroud covered the lower part of the helmet and was attached around the subject's neck. Ocular torsion (OT) was measured from photographs taken by a Nikon F-3 camera using a ring flash attached to the inside of the helmet (Lichtenberg et al., 1982).

Photographs were taken at 2.5 frames per second, which was sufficient to recover the overall sinusoidal motion without aliasing as explained below, but which could not reproduce the higher frequency torsional saccades. The radially symmetric ring flash reduced visual cues of rotational orientation in roll. A biteboard carrying a head fixed reference in the view of the camera enabled measurement of and correction for any residual head movement within the helmet.

Various steps were taken to reduce non-vestibular motion cues. Wind cues were eliminated by having the subject wear gloves and appropriate clothing such that no skin was exposed. Auditory cues were reduced by added white noise and by the sound of a ventilation fan within the helmet. Non-vestibular motion cues were reduced by the tight constraints of the adjustable harness belts, shoulder, forehead, and chin restraints holding the torso, limbs and head against the cushioned seat and helmet. Vibration associated with sled motion along the rails was reduced by mounting the chair on shock absorbers which attenuated vibrations above 30 Hz. Vision was eliminated, when appropriate, by a light-tight shroud over the helmet.

Perception of Linear Motion: This test measured a subject's ability to detect the presence and direction of small changes in linear acceleration. Starting at the center or end of the track, a step acceleration was applied to the cart. After travelling one quarter of the track, a step deceleration was applied which brought the cart to rest at the end or center of the track. Thirteen step accelerations ranging from 0.001 g to 0.08 g (approximately logarithmically spaced) were presented in a random order, once in each direction for each acceleration level. When the subject detected his direction of acceleration, he indicated this by displacing the hand-held joystick in the direction of subjective acceleration. The time delay between actual and indicated change in

acceleration was measured as the time-to-detect. For all but the lowest accelerations, the time to detect small linear acceleration steps varied inversely with the size of the step, such that the product of acceleration and time-to-detect was a constant, analogous to the Mulder product for rotational motion (Young and Meiry, 1968; Melvill Jones and Young, 1978). This product, V, referred to as the velocity constant is one measurement of sensitivity to linear motion. It was determined from a linear regression of time-to-detect vs inverse acceleration for correct responses above 0.005 g:

$$V = A(T_d - T_r)$$

where T_d is the time to correctly detect an acceleration step of magnitude A, and T_r is the effective constant reaction time (Incorrect responses occur when the subject indicated acceleration in the direction opposite the actual acceleration or when the subject failed to indicate any acceleration at all. False positive responses, or guesses, were discouraged and were usually easily identified by their timing and eliminated.). For a given trial of thirteen levels presented randomly, we define threshold to be the lowest acceleration level for which the subject correctly detects three out of four runs at that level and above.

Closed Loop Otolith Assessment Test (CLOAT): This test measured a subject's ability to use linear acceleration cues to perform a manual control task (Zacharias and Young, 1981). During CLOAT the subject made use of otolith sensory information in a closed loop sensorimotor nulling task where the motor function (hand manipulation of a joystick) was presumed relatively unaffected by exposure to weightlessness. The subject was in

control of sled velocity using a joystick. A disturbance motion was generated by the computer and combined with the subject's control. The disturbance consisted of a zero-mean, random appearing velocity profile made up of 12 logarithmically spaced sinusoids added together lasting 82 s. The frequencies of the sinusoids ranged from 0.06 Hz to 0.5 Hz. The subject's task was to try to null the disturbance motion and hold the cart still, thereby closing the loop. CLOAT was performed once in the light and three times in the dark each test session. The resultant sled velocity profiles in the dark were averaged in the frequency domain before further analysis was performed.

In the analysis of CLOAT, motion of the cart which occured during the nulling task was compared to what the sled motion would have been in the absence of any nulling by the subject (i.e. disturbance motion alone) (Hiltner, 1983).

The disturbance velocity, d(t), is given by

$$d(t) = \sum_{i=1}^{12} D_i \sin\left(\frac{h_i}{T} + \phi_i\right)$$

where: D_i is the amplitude of each sinusoidal component as specified in Table 1;

T is the period, or duration of the disturbance (82 s);

h_i is a series of integer primes such that the disturbance frequencies (h_1/T, h_2/T, ..., h_{12}/T) are not harmonics of each other;

ϕ_i is an arbitrarily adjusted phase for each component used to condition the disturbance to achieve maximum excursions, velocities, and accelerations suited to the experimental objectives and to the limitations of the U.S. Labsled.

The sled velocity, r(t), included the result of the subject's efforts to null the disturbance. Fourier analysis was applied to obtain a sled

velocity spectral amplitude, R_i, at each of the frequencies in the disturbance. For a given component frequency, h_i/T, the nulling achieved by the subject at that frequency was measured by the difference between the disturbance amplitude, D_i, and the response, R_i. A cumulative performance measure, referred to as the scalar performance measure (SPM), was derived from the spectral analysis by linear combination of the nulling at each frequency.

$$SPM = \sum_{i=1}^{12} (D_i - R_i)$$

The SPM was judged to be more sensitive to observed performance than usual measures in the time domain, such as RMS or peak response (Hiltner, 1983).

Dynamic Ocular Torsion: This test isolated the gravitoinertial contribution to dynamic ocular counterroling The inability to distinguish between gravitational and inertial forces results in an ocular torsion response to lateral acceleration with the head upright (Baarsma and Collewijn, 1975; Lichtenberg et al, 1982). In this case, the gravitoinertial force vector, rather than the pure gravitational force vector, is rotated with respect to the head. The orientation of the head remains fixed and no rotational accelerations impinge on the head. Sinusoidal oscillation of amplitude 0.61 g was used at two frequencies, 0.42 Hz and 0.83 Hz, for 12 and 25 cycles, respectively. Torsional eye position was obtained by correlation and trigonometric analysis of eye and head position in photographs obtained with a motor driven Nikon F3 camera and ring flash using a 55mm lens and color positive ASA 400 film (Lichtenberg et al., 1982). Photographs were taken at a rate of 2.5 frames per second. This sampling rate was high enough to avoid aliasing from responses to the two stimulus frequencies or their harmonics. Subsequent

video monitoring of OT at the same sled acceleration and frequencies revealed no torsional nystagmus, which might produce false measurement of torsion below 1.25Hz (Nyquist freqency). Eye torsional position was derived from two landmarks (I_1 and I_2) obtained from either naturally occurring landmarks in the iris or marked contact lenses adhered to the eye by application of a drop of distilled water (Edelman, 1979, Kenyon, 1986). Head roll position was obtained from fiducial marks (F_1 and F_2) on extensions of a dental biteboard which appeared in the field of view of the film frame. Cartesian coordinates of points on the photograph ((x_{I1}, y_{I1}), (x_{I2}, y_{I2}), (x_{F1}, y_{F1}), (x_{F2}, y_{F2})) were obtained manually using a Hermes Senior film analyzer in conjunction with a PDP-8 minicomputer. Torsional eye position relative to the head for each frame is given by

$$\theta = \tan^{-1} \frac{(y_{I2} - y_{I1})}{(x_{I2} - x_{I1})} - \tan^{-1} \frac{(y_{F2} - y_{F1})}{(x_{F2} - x_{F1})}$$

The series of torsional eye positions (θ_j) was related to the acceleration stimulus by cross-correlation at the stimulus frequency.

RESULTS

Perception of Motion: Three parameters, a threshold acceleration, a velocity constant, and the regression coefficient associated with determining the velocity constant, were derived from the results of an individual trial consisting of the random presentation of thirteen acceleration levels. Depending on conditions during each sled test session, one or two trials of thirteen acceleration profiles were completed. An additional day of testing at the F-64 preflight session provided a third trial for subject B and a third and fourth trial for subject A. In all, eight preflight trials were conducted with subject A and six trials with each of subjects B, C, and D. In general, preflight

measures showed fairly stable measures of velocity constant (typical correlation coefficients greater than 0.9) with values (typically 6.5 cm/sec) generally lower than previously reported values for x and z axis accelerations (Melville Jones and Young, 1978). (Y-axis thresholds were reported to be lower than x and z by Travis and Dodge (1928), cited by Guedry (1974)) Preflight measures of threshold were more variable than velocity constants on a trial by trial basis. Since the determination of threshold in a given trial is very sensitive to a single detection error, the lowest threshold obtained from among the trials in a particular session was used as the indicator of threshold for that day. Using this latter criterion, preflight thresholds were in the range of 0.002 g to 0.004 g with the exception of subject A in one preflight trial (in the last preflight session, he had a lowest threshold of 0.006 g).

Postflight, measures of both velocity constant and threshold tended to be more variable than the preflight baseline. The increased variability is best seen in the individual responses from which the scalar measures are derived (figure 1). In general, much more scatter is observed in the individual time-to-detect values in the early postflight sessions. This tends to disappear in the later postflight sessions, indicating a return to the preflight baseline. This is also reflected in the correlation coefficients associated with the derivation of the velocity constants (table 2). The increased variability postflight is apparent in the threshold values, although a return to the preflight baseline is not evident in the late postflight sessions (figure 2). The high threshold value observed in subject C on R+4 is probably attributable to extreme fatigue. (The subject fell asleep early in the sled session and the session was not completed.)

CLOAT: CLOAT reflects the individual manual control strategies of the subjects who perform it. Each of the four crewmen tended to have his own control strategy which developed in the early preflight sessions. Performance stabilized in the late preflight sessions for subjects A and B. For each crewman, performance in the dark and in the light improved over the first three preflight sessions. Since this learning effect was reflected in both the dark and light, results from the early preflight sessions were not included in determining the preflight baseline.

Performance was determined by the scalar performance measure (SPM), a single parameter value derived in the frequency domain and described above. Performance, as measured by the SPM, is shown for both preflight and postflight in figure 3. For CLOAT in the light, little change is exhibited between preflight and postflight. The SPM for CLOAT in the light is the result of one trial at each session. Because of the more variable performance in the dark, the SPM for CLOAT in the dark is the average of three trials performed during the same session. Following his relatively stable preflight baseline, subject B performed significantly better postflight ($p < .005$) on both R+0 and R+1. Subject A also performed somewhat better than his preflight baseline ($p < 0.1$) on R+1 and R+2. Subject C showed somewhat better performance on both R+1 and R+2, but not significantly because of the his enhanced performance preflight on L-43. Subject D produced the most erratic results both preflight and postflight. After showing the usual learning effect in both the light and dark during the first preflight sessions, his subsequent preflight sessions showed a decrement in performance in both the light and dark. Postflight, performance in the dark was poorest on R+1, about equivalent to the final preflight session. Performance in the dark on R+2 was the best of all sessions preflight and postflight, with subsequent decrements on R+4 and

R+6.

When the nulling performance is examined at each frequency most of the postflight improvement in the SPM for CLOAT in the dark appears to come from the higher frequencies (0.1 to 0.5 Hz) in the disturbance (figure 4). Dynamic Ocular Torsion: Only the photographic torsion records of subjects A and B have been fully analyzed. At each test session the folded torsion measurements (overlaying each cycle) were highly correlated to the sinusoidal stimulus frequency (figure 5). The fitted sinusoidal amplitude, however, showed high variance from one preflight session to the next in the same subject. One outlying point among the preflight torsion amplitudes increased the variance of the preflight baseline for both subjects at high and low frequencies (figure 6). This obscured any statistical significance in an apparent trend in the postflight measurements. In each case, the first measurement postflight (high frequency, 0.83 Hz., and low frequency, 0.42 Hz., on R+0 for subjects A and B) had an amplitude smaller than or equal to three of the four preflight measurements in the same subject at the same frequency. Subsequent amplitude measurements postflight (R+1, R+2, R+4, and R+6) increased monotonically for both subjects at both frequencies with the exception of one data point (subject A, low frequency, R+6). Subject B exhibited the greater tendency to diminished ocular torsion amplitude postflight. (He also had shown the greatest tendency to enhanced performance postflight in CLOAT.)

DISCUSSION

Otolith mediated responses to pure linear acceleration are central to studies of vestibular adaptation to weightlessness because of the inability to distinguish between linear acceleration and gravitational force. Our

hypothesis (Young et al., 1984, 1986) relating to the nervous system's reinterpretation of otolith mediated signals, predicts that inflight the perception and postural reactions to angular and linear acceleration might be altered, as otolith cues are selectively ignored and/or reinterpreted. Preflight/postflight tests of linear acceleration responses permitted us to estimate the extent to which any inflight adaptation might carry over to postflight alterations. The preflight/postflight sled test results presented in this paper suffer from a high level of variability in the preflight measurements, a small numbers of repetitions, and the lack of substantial testing immediately upon return. All of these problems should be ameliorated with continued Spacelab testing and especially with the planned inflight sled measurements scheduled for the German Spacelab Mission.*

The time to detect steps of lateral horizontal acceleration in these subjects shows generally the same pattern which is seen in the normal population, although with considerably lower velocity constants (higher sensitivity) (Melvill Jones and Young, 1978). Despite the similarity of overall response times vs acceleration level between preflight and postflight, a close examination of the limited early postflight records provides some interesting observations. On the first test opportunity following landing, each subject appeared to be more erratic in his detection in some regard. This did not consistently lead to either a lowered threshold or velocity constant as might be expected from the otolith reinterpretation hypothesis. It did reveal some errors in direction at even higher acceleration levels and some correct detection of very low accelerations. The general impression, not supported

*These experiments were conducted in November 1985. Preliminary results on the CLOAT support the findings in this paper.

statistically, was of a highly sensitive but noisy accelerometer system being used by the crew for judging lateral acceleration after landing. The concept of a simple threshold for linear acceleration detection, whether or not one accounts for the correctness of the direction, is of dubious value in these cases. A more valid approach is to consider detection of vestibular stimuli as a signal detection or signal-in-noise problem (Ormsby and Young, 1977). Considering the detection results of this study, along with those reported on the same crew by Benson (1984) using different protocols and equipment, we suggest that the postflight alteration in otolith function, as it affects acceleration detection, is a possible decrease in effective signal to noise ratio along with an increase in sensitivity. The different responses of the individual crew members could relate to their own particular detection criteria. Further postflight measurements on future crew members should clarify this issue.

The general ability of crew members to perform better on the non-visual closed loop lateral acceleration nulling task postflight was surprising in view of their poor postural stability with eyes closed at the same period (Kenyon and Young, 1986). Two of the four crewmen (A + B) performed better than ever before on R + 0 and R + 1. One crewman (C) performed better on R + 1 and R + 2 than in all but one of the 5 preflight measurements. The fourth crewman (D) showed deteriorated performance on R + 1 but had his best performance on R + 2.Despite the preflight variablity in this measure, which precludes the drawing of strong statistically valid conclusions, the observations suggest that the crew returned to earth capable of sensing and reacting to lateral acceleration more effectively than preflight as long as they did not need to stablize their trunk with respect to gravity. This ability, to use otolith information effectively to control translation, but not to control tilt, is just what would be

appropriate for posture control in weightlessness. It forms part of the support for the tilt-translation reinterpretation hypothesis which predicts a selective enhancement of responses which interpret lateral gravitoinertial force as linear acceleration and a dimunition of responses in which it is interpreted as tilt of the head with respect to gravity.

The dynamic ocular counterrolling tests were carried out at two frequencies to complement the static OCR tests. The experiment was designed to see if the anticipated reduction in OCR associated with otolith tilt reinterpretation would be frequency dependent, with a greater gain decrement at low frequencies than at the higher frequencies associated also with translation transients. Once again, large preflight test-to-test variability limits our ability to draw statistically valid conclusions. However for both subjects analyzed, the first postflight OCR gain was lower then the measured gains on subsequent postflight days, or on the last preflight day, at both high and low frequencies. The occasional other low values of OCR gains measured preflight cannot be explained. When considered in conjuction with the findings of von Baumgarten et al. (1984) concerning reduced static OCR gains postflight, these possible dynamic reductions also support the tilt-translation reinterpretation hypothesis in general and suggest that the tilt gain reduction occurs at a level so basic as to affect even the elementary ocular counterrolling reflex.

In summary, while trends in the results are supportive of the tilt-translation reinterpretation hypothesis, the small sample (n=4) obtained from the Spacelab 1 Mission precludes any clear conclusions. Repetition of these tests with the crews of the German Spacelab Mission and the Dedicated Life Sciences Mission should aid in the clarification. Of particular

interest are the apparent decrease in dynamic ocular torsion (a tilt response) and the apparent increase in CLOAT performance (a translation response) in some of the crewmen.

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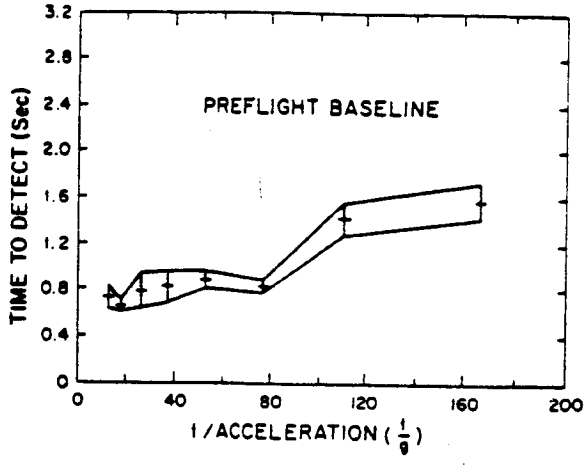
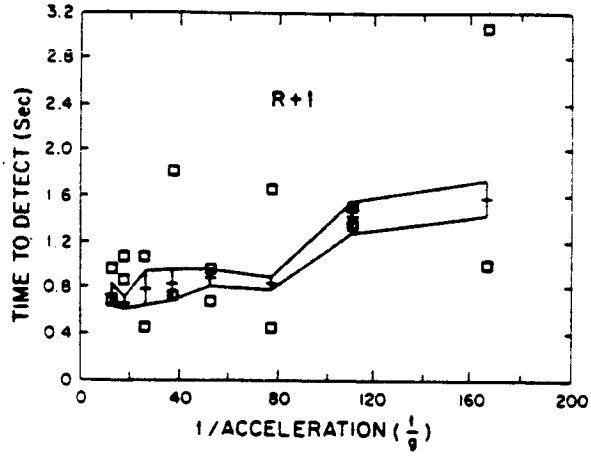
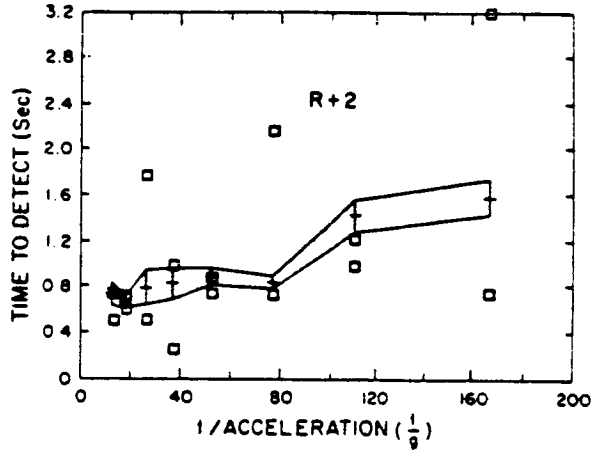
Figure 1.

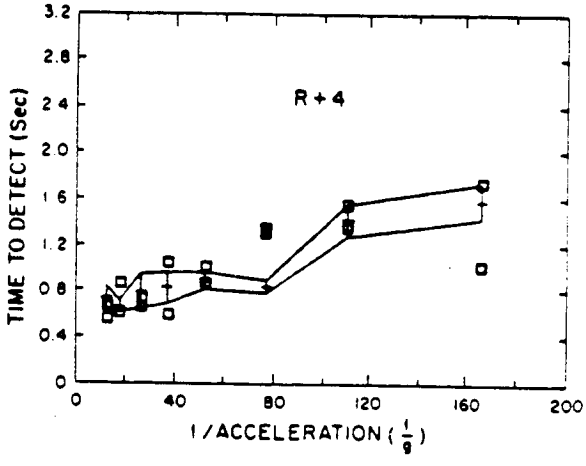
The delay between the application and subjective perception of small acceleration steps (0.005 to 0.08 g) is plotted against the inverse of the size of the step. Squares indicate the detection times measured 1, 2, 4, and 6 days after ten days in weightlessness for subject A. Error bars connected by lines indicate the preflight mean and ± 1 standard deviation for subject A. The trend towards less scatter by 4 days postflight was observed in all subjects, as was the somewhat increased scatter at 6 days postflight.

Figure 1


PREFLIGHT BASELINE
TIME TO DETECT (Sec)
1/ACCELERATION (1/g)


R+1
TIME TO DETECT (Sec)
1/ACCELERATION (1/g)


R+2
TIME TO DETECT (Sec)
1/ACCELERATION (1/g)


R+4
TIME TO DETECT (Sec)
1/ACCELERATION (1/g)

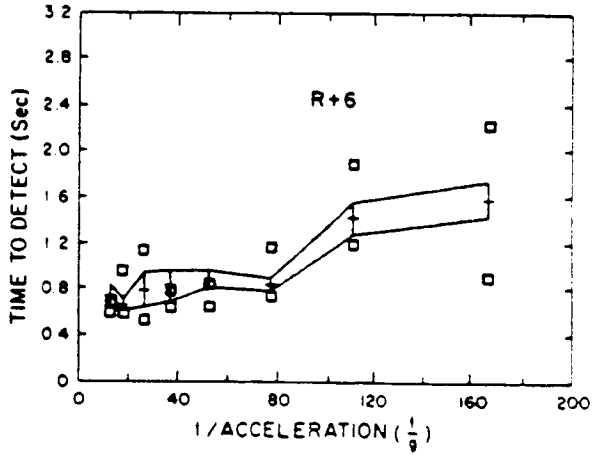

R+6
TIME TO DETECT (Sec)
1/ACCELERATION (1/g)

Figure 2.

The lowest value for the threshold of perception of acceleration obtained during each session is shown for the last three sessions preflight (64, 43, and 10 days before launch) and for the days immediately following ten days in weightlessness. The high variability and lack of consistent pattern among the results obtained from the four crewmen postflight is in contrast to the consistent repeatable results obtained preflight.

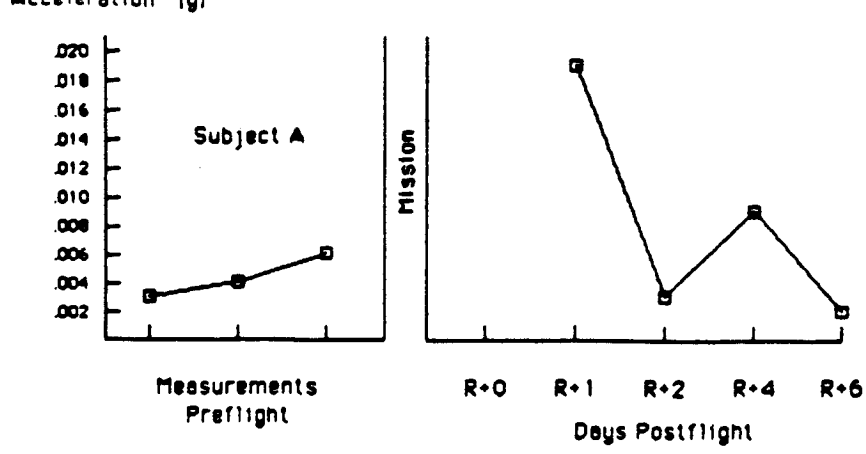
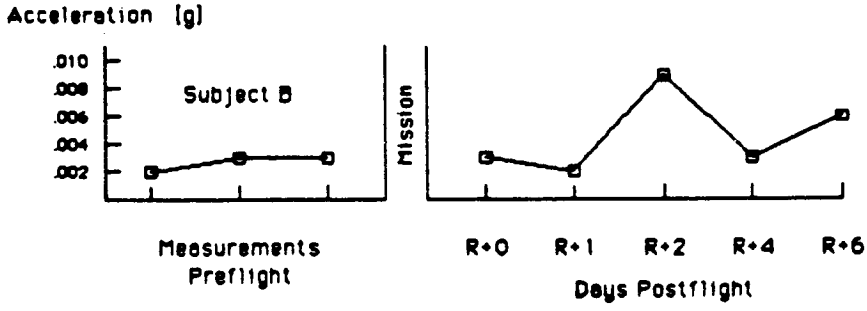
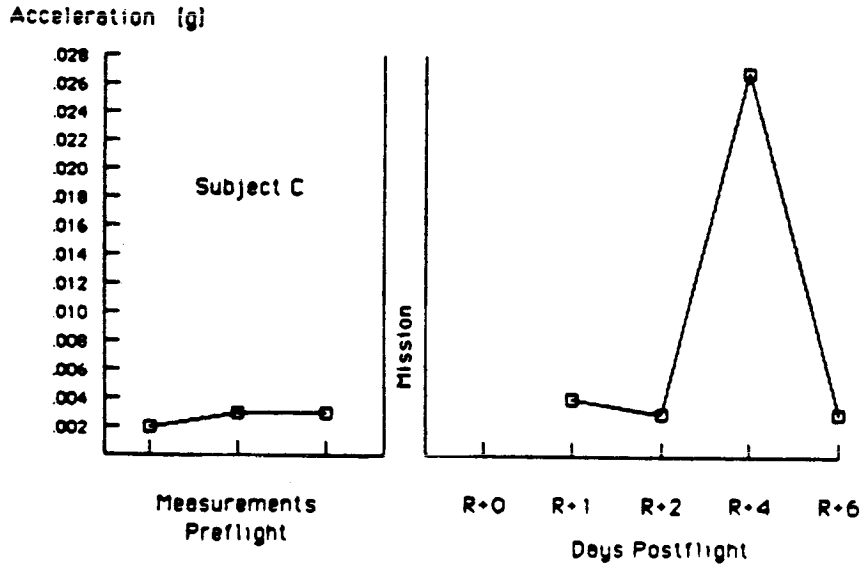

Acceleration [g]
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
Subject A
Mission
Measurements
Preflight
R+0
R+1
R+2
R+4
R+6
Days Postflight

Figure 2.


Acceleration [g]
.010
.008
.006
.004
.002
Subject B
Mission
Measurements
Preflight
R+0
R+1
R+2
R+4
R+6
Days Postflight


Acceleration [g]
.028
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
Subject C
Mission
Measurements
Preflight
R+0
R+1
R+2
R+4
R+6
Days Postflight

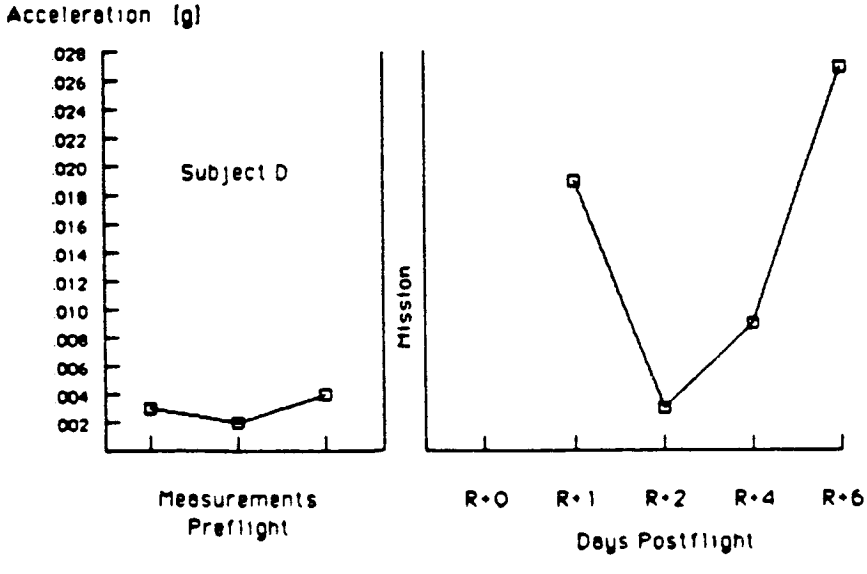

Acceleration [g]
.028
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
Subject D
Mission
Measurements
Preflight
R+0
R+1
R+2
R+4
R+6
Days Postflight

Figure 3.

The scalar performance measures (SPM) derived from CLOAT trials at each test session are diplayed for CLOAT performed in the light (filled circles) and in the dark (error bars). SPM in the dark is shown as the average of three trials with ± 1 standard deviation.

Figure 3.

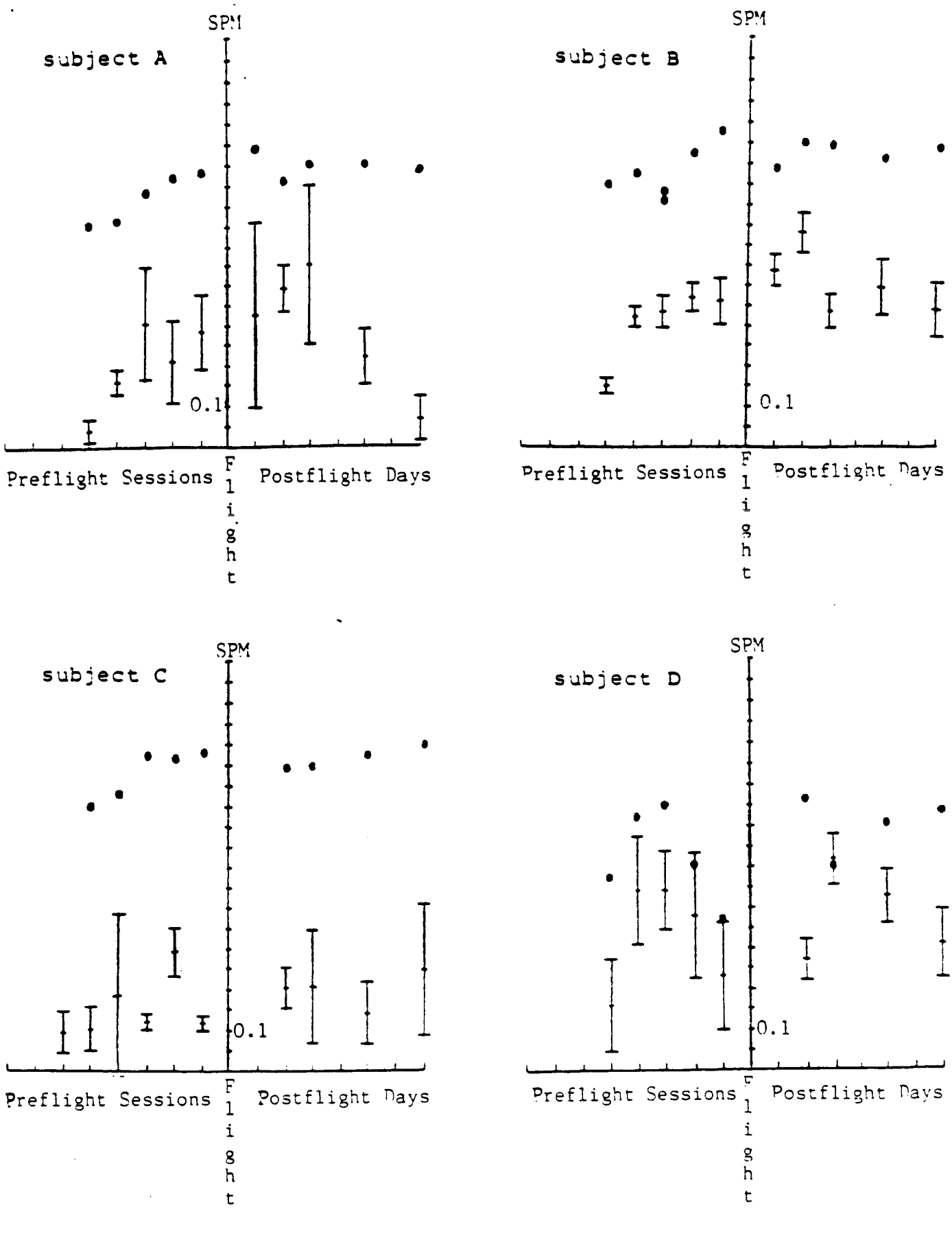
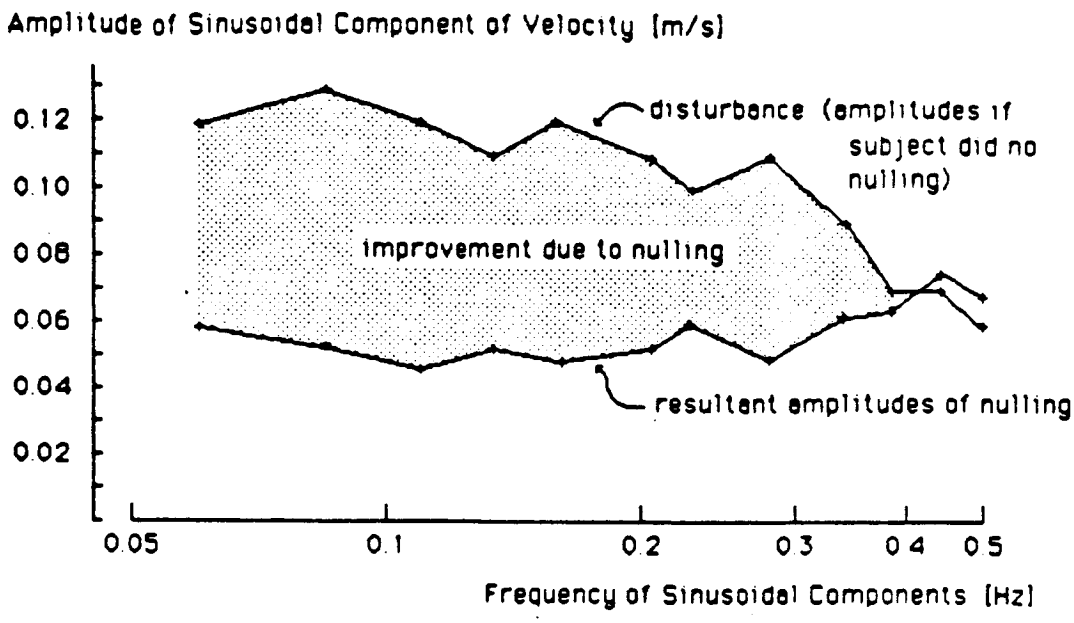
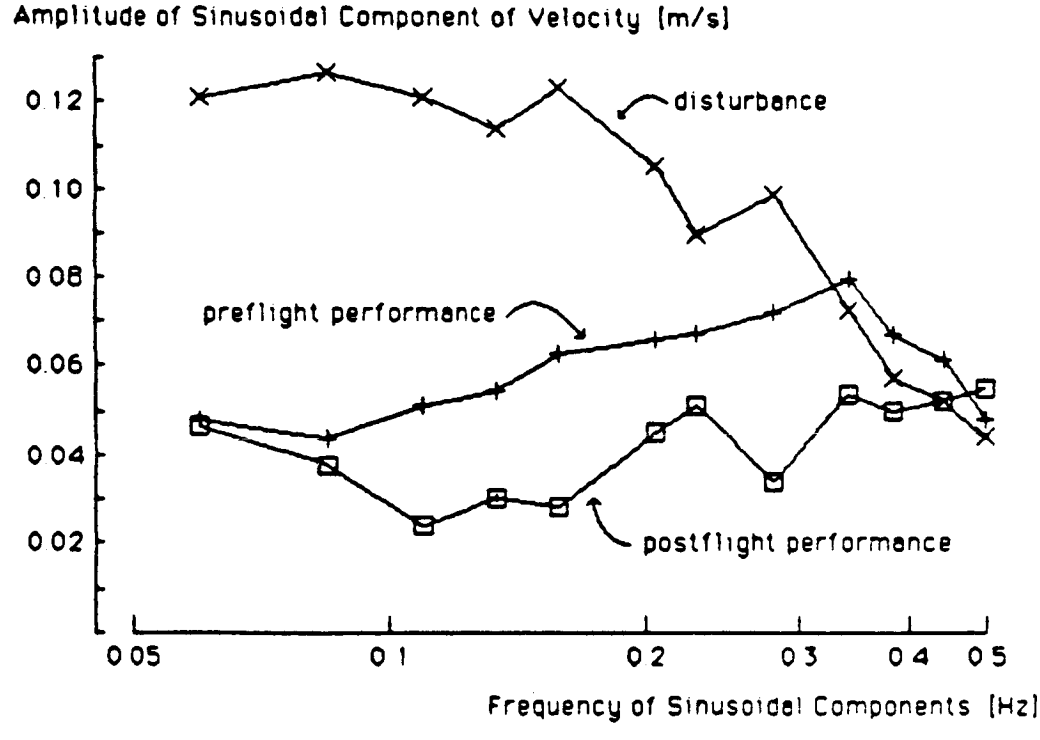

subject A
SPM
0.1
Preflight Sessions
Flight
Postflight Days
subject B
SPM
0.1
Preflight Sessions
Flight
Postflight Days
subject C
SPM
0.1
Preflight Sessions
Flight
Postflight Days
subject D
SPM
0.1
Preflight Sessions
Flight
Postflight Days

Figure 4.

In the upper graph results of a typical CLOAT are shown in the frequency domain. Velocity amplitudes at the discrete frequencies which make up the sum of sines disturbance are shown for both the velocity of the disturbance and the velocity of the sled resulting from the subject's effort to null his motion. The shaded area between the two curves represents the amount by which the subject has reduced sled motion. In the lower graph the disturbance amplitudes are indicated by (X), the preflight average performance for subject B is indicated by (+). The postflight performance for subject B at 24 hours after landing is indicated by (□). To the extent improvement in CLOAT was observed in other crewmen, it was primarily in the same frequency range observed here (0.1 to 0.4 Hz.).

Figure 4.





× disturbance (amplitudes if subject did no nulling)

\+ nulling performance preflight

□ nulling performance 24 hours postflight

Figure 5.

In the upper trace ocular torsion for the left and right eyes is shown in relation to the acceleration stimulus. Each point represents the mean and ± 1 standard deviation of repeated measurements obtained from one photograph of both eyes. In the lower traces, ocular torsion is shown as a function of phase of the sinusiodal motion stimulus cycle, effectively folding the time series into a single cycle.

Figure 5.

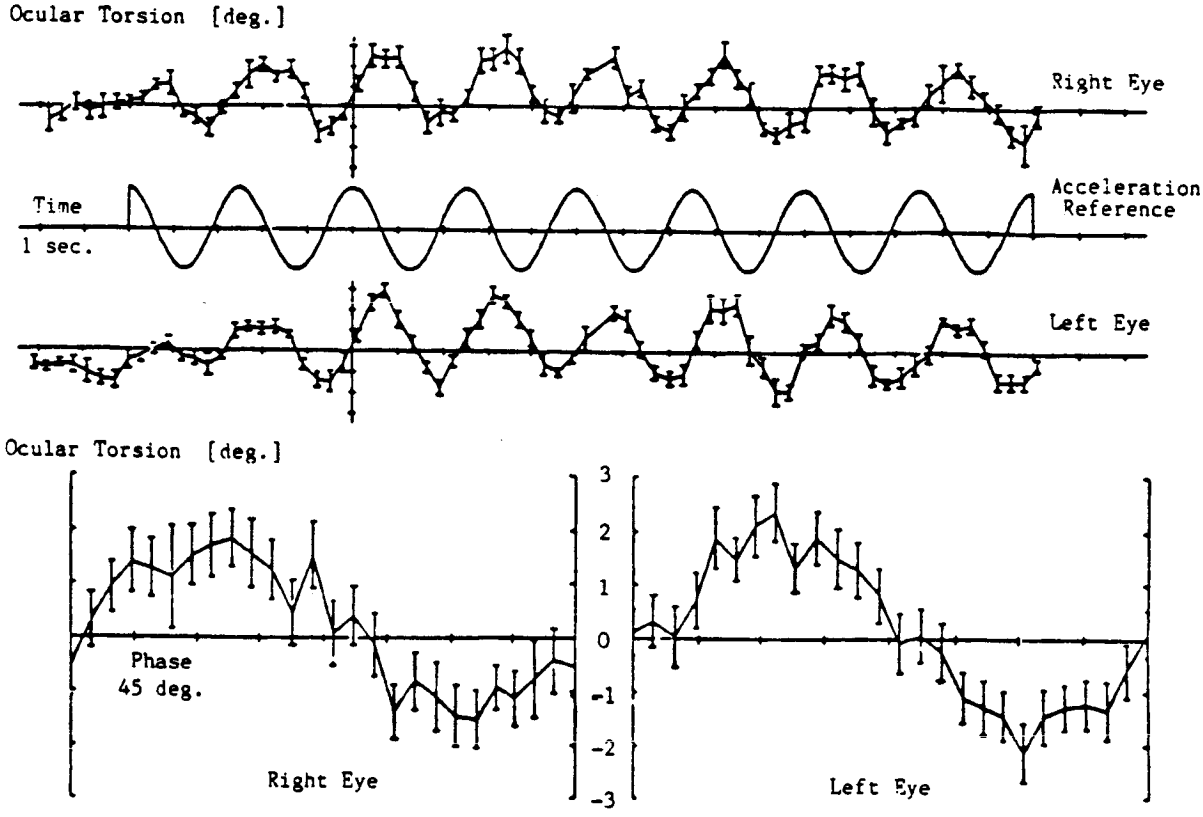
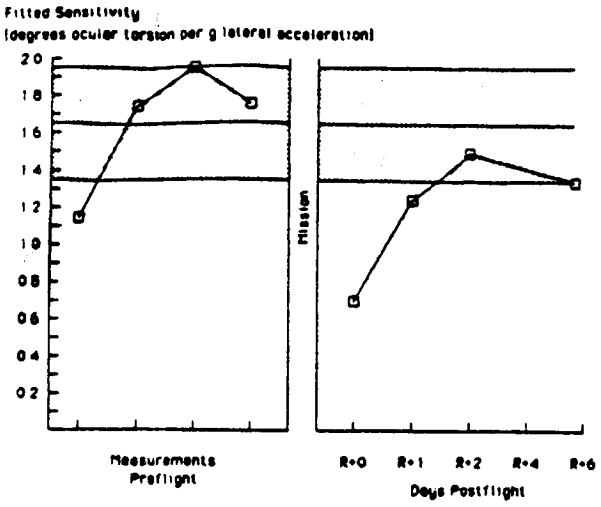

Ocular Torsion [deg.]
Right Eye
Time
1 sec.
Acceleration Reference
Left Eye
Ocular Torsion [deg.]
3
2
1
0
-1
-2
-3
Phase
45 deg.
Right Eye
Left Eye
Phase Relative to Stimulus [deg.]

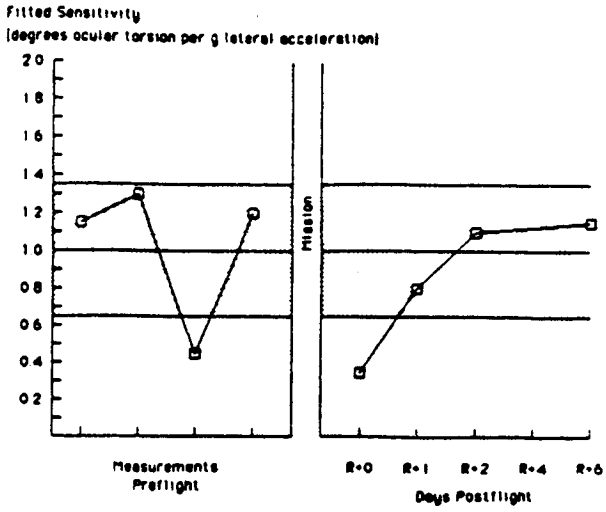
Figure 6.

The fitted sinusoidal amplitude of ocular torsion is shown for measurements made before and after exposure to ten days of weightlessness. The solid lines are the mean and ± 1 standard deviation of the measurements obtained preflight. Postflight measurements for subjects A and B at 6 hours after landing and then 1, 2, 4, and 6 days after landing are displayed in relation to the preflight mean and standard deviation. Two frequencies of the sinusoidal motion stimulus were used: 0.42 Hz. and 0.83 Hz.

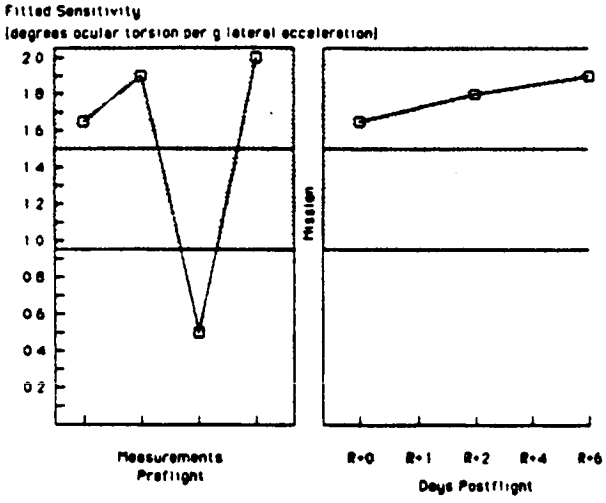
Figure 6



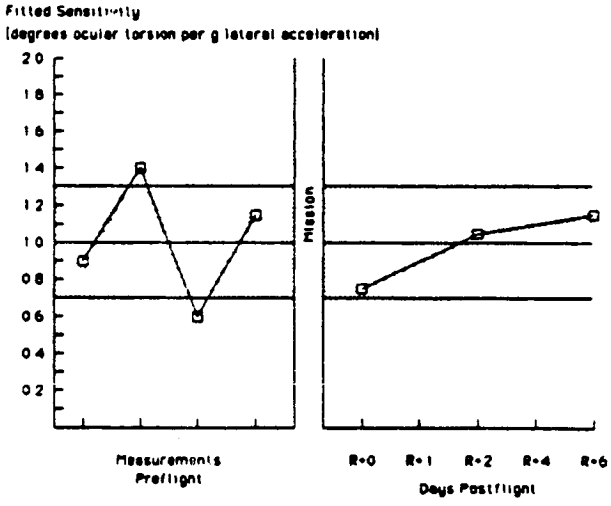
Subject A Low Frequency Oscillation (0.42 Hz)



Subject A High Frequency Oscillation (0.83 Hz)



Subject B Low Frequency Oscillation (0.42 Hz)



Subject B High Frequency Oscillation (0.83 Hz)